Supply Chain Management Ontology from an Ontology Engineering Perspective

Andreas Scheuermann, Joerg Leukel
University of Hohenheim, Schwerzstr. 35, 70599 Stuttgart, Germany
E-mail: andreas.scheuermann@uni-hohenheim.de, joerg.leukel@uni-hohenheim.de

Abstract. Knowledge sharing and reuse are important factors affecting the performance of supply chains. These factors can be amplified in information systems by supply chain management (SCM) ontology. The literature provides various SCM ontologies for a range of industries and tasks. Although many studies make claims of the benefits of SCM ontology, it is unclear to what degree the development of these ontologies is informed by research outcomes from the ontology engineering field. This field has produced a set of specific engineering techniques, which are supposed to help developing quality ontologies. This article reports a study that assesses the adoption of ontology engineering techniques in 16 SCM ontologies. Based on these findings, several implications for research as well as SCM ontology adoption are articulated.

Keywords: supply chain management; ontology; ontology engineering; knowledge sharing; information systems; literature review

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1 Introduction

The premise of supply chain management (SCM) is that the performance of a single company depends more and more on its ability to maintain effective and efficient relationships with its suppliers and customers [1],[2]. Therefore, managerial tasks are moving from an organizational scale to a supply chain scale [3] and thus encompass the inter-organizational integration and coordination of dispersed supply chain activities. Empirical research suggests that knowledge sharing and reuse between supply chain participants are important determinants of supply chain performance at both the strategic and operational level [4],[5]. The role of information systems to support this task is subject of much research [6],[7],[8].

Knowledge sharing and reuse between supply chain participants face many organizational obstacles such as confidentiality, trust, and norms. However, fundamental prerequisites for knowledge sharing are means for exchanging, processing, and interpreting the relevant domain knowledge by using one or more representations of this knowledge. Since such representations may be diverse and serve different objectives, formal ontology has been proposed as an important means to represent domain knowledge, enhance communication between participants, and support interoperability of systems [9]. A formal ontology formally captures knowledge through concepts, relationships and axioms, and can be regarded as the conceptual model of a knowledge base [10]. The application of ontology in SCM has led to a large number of ontologies for various SCM tasks, e.g., planning [11] as well as more generally representing arbitrary supply chains [12].

Although researchers make use of ontology specifically for SCM, this stream of research seems to be less connected with the ontology engineering (OE) field as it could be. Over the past 20 years, the OE field made significant advances with regard to its constructs, models, methods, and tools, and contributes specific techniques that assist ontology developers [13],[14]. However, the extant literature does not inform us sufficiently about the concrete linkages between OE and SCM ontology. In particular, little is known to what extent the development of these ontologies is informed by the techniques available from this field. The first steps to increasing our knowledge about these ties were taken by Grubic and Fan [15], who review six supply chain ontologies: Two out of five evaluation criteria used in their review concern the methodological foundation as follows. “Scientific paradigm” studies the epistemological stance of the ontology researcher. “Methodological approach” studies the adoption of five general approaches to ontology design that were proposed in [16]. Our review complements and extends this research by (1) studying the adoption of concrete techniques from the OE literature and (2) reviewing a larger set of in total 16 SCM ontologies of which three are also found in the study by Grubic and Fan [15].

While empirical research has contributed to understanding the applicability and usefulness of OE techniques [17],[18], assessing their adoption in concrete ontologies has received little attention. Therefore, the objective of this article is to review and analyze current SCM ontologies with regard to their methodological foundation, i.e., the adoption of OE techniques. This study concerns the concrete linkages between OE techniques and SCM ontology as a particular type of application ontology. It contributes to understanding these linkages and motivates avenues of future research.

This article proceeds as follows. The theoretical background to the review is described in section 2. The review process and the relevant SCM ontologies are presented in section 3. The review results can be found in section 4. The discussion of the findings and their implications for future research are part of section 5. A summary of the research is given in section 6.

2 Theoretical Background

2.1 Formal Ontology

Originally, the term ontology has its roots in philosophy. As a discipline of philosophy, ontology denotes "the science of what is, of the kinds and structures of objects, properties events, processes, and relations in every area of reality" [19]. Starting in the late 1980s and early 1990s, ontology gained increasing awareness in Computer Science and Artificial Intelligence (AI). AI requires formal representations of real world phenomena in order to reason about these phenomena. In a literal sense, AI research borrowed the term ontology from philosophy and equipped it with a computational meaning. As a result, AI coined the term "formal ontology" (or computational ontology). The key characteristics of formal ontology are part of the definition coined by Studer et al. [20]: Ontology is "a formal, explicit specification of a shared conceptualization of a domain of interest". Conceptualization depicts an abstract representation of some (real-world) phenomenon by having determined its relevant concepts, relationships, axioms, and constraints. Further, explicit denotes the explicit (not implicit) definition of the type of concepts, relationships, axioms, and the constraints holding on their use. Formal indicates that the ontology should be readable and interpretable by machines, thus formal excludes the use of natural language. Finally, shared conceptualization requires the ontology to capture consensual knowledge that is not private to an individual person but accepted by a larger group of individuals.

SCM is a particular field of application for ontology, which results into SCM ontology. To determine the scope of our analysis, it is necessary to qualify this kind of ontology in more detail. We refer to the classification proposed by Guarino [10], which categorizes ontologies by the level of generality into four types:

- *Top-level ontology* specifies a conceptualization that is independent of a particular domain; for instance, it concerns space, time, object, and event.
- *Task ontology* defines the vocabulary related to a particular type of task such as planning, diagnosing, or purchasing. This type of ontology defines the task knowledge that is required for solving a particular type of task.
- *Domain ontology* defines the vocabulary related to a particular domain such as healthcare, automotive, or machinery.
- *Application ontology* provides the vocabulary that depends both on a particularly task and domain, e.g., clinical pathway design, general inspection, or production planning.

Using this classification, SCM ontology belongs to application ontology, with supply chain being the domain and operations spanning a wide array of tasks. It should be noted that task ontologies have also been proposed for supply chain planning. These task ontologies are, however, not subject of our study but have been analyzed in prior research [21].

2.2 Ontology Engineering

Ontology engineering is a field within the knowledge engineering discipline. Whereas the latter is concerned with knowledge-based systems, OE "investigates the principles, methods and tools for initiating, developing, and maintaining ontologies" [22]. Ontologies can be a component of knowledge-based systems, but also provide a "common language" for communication between domain analysts, developers, and users. The fundamental premise is that OE as a collective, non-observable construct positively affects the quality of the produced ontology [23]. Through this quality, OE indirectly contributes to the task performance of either knowledge-based systems or people who use the ontology for specific tasks. The main impediment to measuring the supposed relationship between the OE construct and task performance is that the quality of an ontology is a complex, multi-facet property, which is difficult and costly to asses or objectively not feasible at all [24].

Ontology quality is still subject of much research in OE [25]. Empirical studies that use concrete measurements and involve ontology users are scarce. Most research is concerned with the syntactic and semantic dimensions of quality [26]. We believe that insights from conceptual modeling research may provide a more appropriate theoretical foundation for the purpose of our study. Specifically, Lindland et al. [27] were the first to integrate syntactic, semantic and pragmatic quality into a framework for quality of modeling scripts, which denote the outcome of the modeling activity. In the context of ontology, the activity is ontology development and the outcome is the ontology. The framework by Lindland et al. draws on linguistics and semiotics theory. In particular, pragmatic quality captures how well the script – respectively ontology – is understood by its users. Pragmatic quality can be assessed by means of comprehension and problem solving tasks. Measures include task accuracy and completion time as well as user perceptions such as confidence in the solution and user satisfaction. In the broader context of task-technology fit, it has been shown that user perceptions are related to task performance [28].

The model of OE is shown in Figure 1. This model articulates the dependencies between OE techniques, user perceptions, and task performance. We restrict the supposed positive effect of OE on pragmatic quality, which is being articulated by *Perceived Usefulness of Ontology (PUO)*, *Perceived Ease of Use of Ontology (PEUO)*. These are adoptions of two common constructs for user perceptions in information systems evaluation. Since we will not perform an empirical measurement, it is not necessary to specify these constructs in more detail. These refinements could adopt extant frameworks for user perceptions in conceptual modeling research; for instance, Maes and Poels [29] propose a framework that reuses constructs and relationships of the information systems success model of DeLone and McLean [30] and its extension by Seddon [31]. The model contains six independent, categorical variables that represent techniques of the OE field as constructs. These constructs are supposed to positively affect the dependent, continuous variables PUO and PEUO, and therefore also task performance.

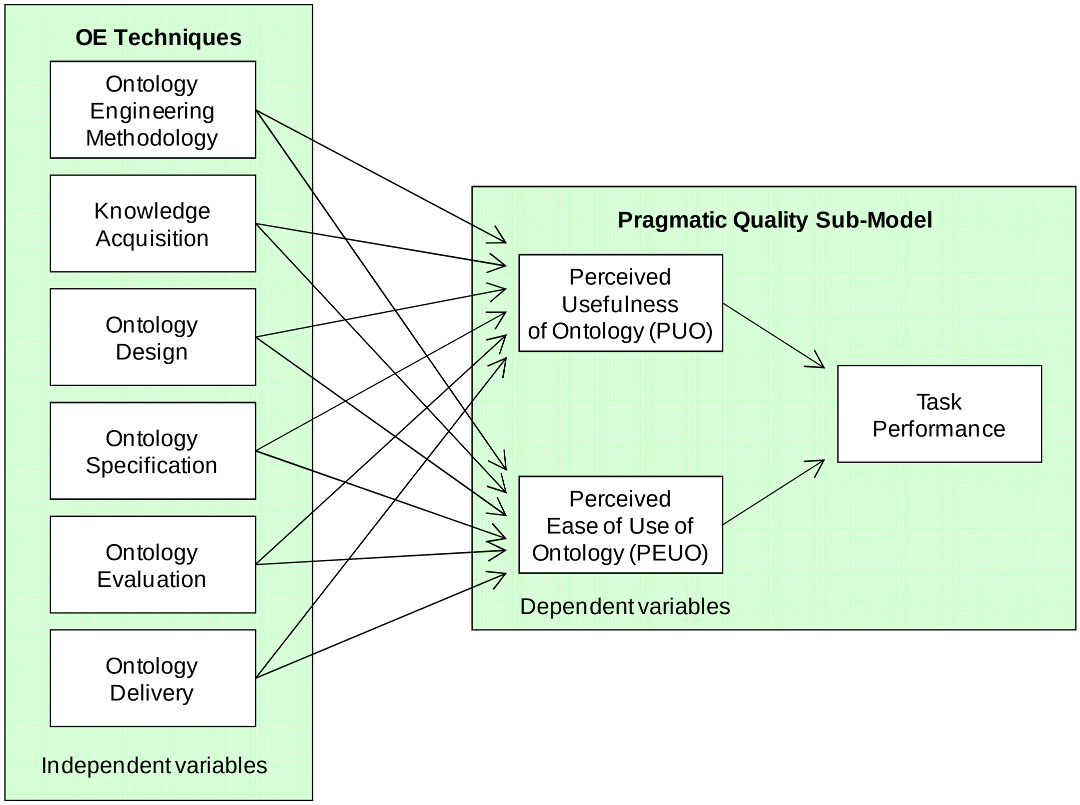

Fig. 1. Model of Ontology Engineering.

2.3 Constructs and Measurements

OE research concentrates very much on novel design artifacts for unsolved organizational and computational problems. Only recently, empirical research has progressed toward understanding the effects of OE on ontology quality. Despite the lack of an original OE theory – which would supply candidate constructs and relationships for our analysis – we argue that the ontology development process provides an initial theoretical underpinning. This process is made of subsequent phases that ontology engineers execute to produce the ontology. We admit that these phases may also be subject of inquiry, but contend that empirical studies in OE provide support for their validity [17],[18]. These phases are implemented through six constructs: *OE Methodology*, *Knowledge Acquisition*, *Ontology Design*, *Ontology Specification*, *Ontology Evaluation*, and *Ontology Delivery*. Next, we will detail each construct by describing its proposed measurements (Table 1). In a prior survey of eight task ontologies for supply chain planning, these constructs and measurements appeared to be useful for assessing the adoption of OE techniques [21]. We think that the constructs and measurements can be applied to both task and application ontology.

Table 1. Constructs and Measurements.

Construct	Measurement
OE Methodology	Ontology New Development Ontology Reengineering Ontology Merging and Alignment Ontology Learning
Knowledge Acquisition	Knowledge Source Knowledge Acquisition Technique
Ontology Design	Ontology Design Principles Ontology Design Patterns Ontology Reuse
Ontology Specification	Ontology Language Knowledge Representation Paradigm
Ontology Evaluation	Evaluation Method
Ontology Delivery	Documentation Availability

2.3.1 OE Methodology

OE methodology is concerned with defining and structuring the development process by means of process models, activities, products, roles, and management tools [23]. Many OE methodologies originate from the knowledge engineering discipline but use elements that are common in software engineering. Similarly to software engineering, a great number of OE methodologies have been proposed. For the purpose of our study, we rescind from concrete process models and their elements, but examine similarities and differences on a higher level of abstraction [32]. The literature distinguishes methodologies for *Ontology New Development* (process of creating a novel ontology without largely reusing an existing ontology), *Ontology Reengineering* (process of fundamentally rethinking the conceptualization of a given ontology), *Ontology Merging and Alignment* (process of unifying two different, though overlapping conceptualizations into one new conceptualization, respectively determining semantic equivalence between a leading and a supplementing conceptualization) and *Ontology Learning* (process of semi-automatically deducing a conceptualization from a given data set).

2.3.2 Knowledge Acquisition

Whereas OE methodology sets the overall development process and defines whether and to what extent it draws on existing conceptualizations, knowledge acquisition is a particular activity within this process. This construct has two measurements: *Knowledge Source* represents the types and instances of sources that are used for acquiring knowledge from the domain of discourse. These types may include domain experts, textbooks, technical articles, and specifications. *Knowledge Acquisition Technique* is the means how to elicit knowledge from these sources. Its objective is to identify and capture the relevant knowledge. A variety of techniques such as text analysis, structured interviews or brainstorming can be applied to different knowledge sources. In particular, domain knowledge has close ties to a human's problem-solving capability and the execution of tasks. Thus, knowledge acquisition techniques must effectively support the conversion and dissociation of tacit and procedural knowledge into explicit and declarative knowledge [33].

2.3.3 Ontology Design

Ontology design supplies techniques that help the ontology engineer in determining the structure of the ontology. These techniques are more specific than OE methodology and have been influenced by experiences acquired in prior ontology engineering projects. Three types of techniques are proposed in the literature: *Ontology Design Principles* are overarching quality criteria in terms of desiderata, i.e., desired properties that the ontology should exhibit, though their direct assessment is difficult and achieving them completely is often not possible. Criteria such as clarity, modularity, and minimal encoding bias were adopted from model quality research. *Ontology Design Patterns* provide basic ontological building blocks for recurring issues of ontology structure, content, and representation [34],[35]. The rationale of these patterns is, again, influenced by patterns in software engineering, which first proposed patterns that abstract from a concrete form and “keep recurring in specific nonarbitrary contexts” [36]. *Ontology Reuse* suggests the adoption of top-level ontologies for specific ontologies [10], e.g., by specializing a top-level ontology’s class with a new domain-specific class.

2.3.4 Ontology Specification

Ontology specification has two distinct, though interrelated measurements. First, *Ontology Language* depicts the grammar or formal language used for specifying the ontology. This language can be selected from a large array of languages that originate from both OE (specific languages for formal ontology) and conceptual modeling. The latter includes languages such as entity-relationship diagram, UML class diagram, object constraint language (OCL), and the many derivates and extensions of these languages that emerged over the past decades. OE research contributes a similarly wide range of languages, e.g., KIF (Knowledge Interchange Format), OCML (Operational Conceptual Modeling Language), DAML-OIL (Darpa Agent Markup Language – Ontology Inference Layer), and OWL (Web Ontology Language). The main difference to conceptual modeling languages is the higher degree of formal semantics, which allows more advanced forms of reasoning on knowledge bases; this characteristic is also called expressivity of the ontology language. Second, we use *Knowledge Representation Paradigm* to indicate the underlying paradigm that the ontology language implements. The three most popular paradigms in OE research are First-order Logic (FOL), Frame Logic (F-logic), and Description Logic (DL) [37]. Each ontology language implements one of those paradigms; for instance, OWL is an implementation of DL. Languages from conceptual modeling rely upon other paradigms such as algebra of sets. The rationale for having two separate measurements is that the relationship between knowledge representation paradigm and ontology language is one-to-many; hence, when a particular ontology adopts a KR paradigm, then it actually may use two or more languages for specification purposes.

2.3.5 Ontology Evaluation

Ontologies must be evaluated with respect to the utility provided for the class of tasks addressed. The evaluation should be integrated into the development process, prior to handing the ontology over to prospective users. Therefore, OE stresses that the utility of the ontology must be demonstrated through well-executed evaluation methods. The ontology evaluation construct is measured through *Evaluation Method*. Evaluation first requires the definition of appropriate metrics, for which respective evaluation methods subsequently can be applied. These metrics concern, as discussed in section II, syntactic, semantic, and pragmatic quality. Syntactic quality can be assessed by analytical (formal) methods that determine the syntactic correctness of the ontology with respect to the ontology language used. Semantic quality concerns the correspondence between the ontology and its domain; it can be studied by descriptive evaluation methods, i.e., constructing detailed scenarios around the ontology to demonstrate its utility, or providing informed arguments that ground on prior research. Pragmatic quality is subject to the correspondence between the ontology and the user's interpretation; thus, respective evaluation methods involve users by means of a case study, field study, or controlled experiment. Alternatively, simulation could be used that processes artificial data as surrogates for users; this data must be justified through valid assumptions about the ontology's users.

2.3.6 Ontology Delivery

Prospective ontology users need sufficient detail to enable the ontology to be used, i.e., implemented in the user's organizational context. Thus, this construct represents the extent and means how the ontology is provided by the engineer. This construct has two main measurements: *Documentation* concerns the types of supplementing documents that are available for ontology users. These documents should help users in assessing the ontology's applicability, understanding the ontology's content, and correctly using the ontology. *Availability* states whether and in what form a machine-processible specification is provided to the user (making the ontology available through a file that can be downloaded at a web site, e.g., public ontology repository).

3 Review Process

A structured approach was employed to identify the relevant SCM ontologies in the literature. A systematic search was used to retrieve publications that describe SCM ontologies. We used citation count as a proxy measure to identify probable core publications. Since filtering based on citation count may exclude some relevant ontologies, an exploratory approach was used to find additional publications on supply chain ontologies. The latter approach allowed us to identify and include some very recent studies [38],[39]. We describe the search approach below.

3.1 Search for SCM Ontologies

Online databases were used for a keyword-based search. Because SCM is an interdisciplinary field, this search included journals and proceedings from related areas such as Operations Management, Information Systems (IS), Conceptual Modeling, and Knowledge Engineering. Scopus was used for its good coverage of journals and Google Scholar for its comprehensive coverage of journals, proceedings, and books. The initial search query of "supply chain" AND "ontology" yielded a total of 274 documents (Scopus), respectively more than 17,400 documents (Google Scholar). The sample was too extensive for an in-depth analysis and contained a large number of documents that are not relevant, e.g., do not report a specific SCM ontology as defined in section 2.1. Therefore, the search was performed in an iterative way by both reducing the list of search results (e.g., adding constraints to the search query) as well as expanding the list (e.g., adding alternative terms to the search query).

As constraints we used citation count (threshold of 10), source type (journal, proceedings), language (English), and subject area. We used alternative terms to reflect the actual use of various terms for the key concepts as follows: “supply network”, “supply chain management”, “logistics”, “data model”, “information model”, “knowledge model”, “semantic model”, “conceptual model”, “ontology model”. This approach led to a much shorter list, which was then manually inspected by analyzing the abstracts and skimming the content, resulting in 16 publications. Each publication makes an original contribution to the field, i.e., proposes a specific and formal ontology for SCM. For instance, we removed the ontology proposed by Lin and Harding [40] as they propose a taxonomy dedicated to the domain of manufacturing for knowledge sharing across engineering teams.

3.2 Coding

Each publication was carefully examined by the two authors who independently coded each reported ontology according to all the constructs and measurements of ontology engineering (section II). The coders discussed conflicting codes until a mutual agreement was reached. Five criteria complement the measurements to capture the focus of each ontology as follows:

- *Users* is concerned with the group of users who use the ontology. User could be either a person that uses the ontology for a problem-solving task (e.g., system design) or an application system that uses the ontology for retrieving, processing and transferring knowledge by accessing the knowledge base (run-time).
- *Scope* is concerned with the branch of industry, sector, or market for which the ontology is to be used. If the publication does not mention a specific limitation, then we assume that the ontology’s scope is not restricted but that of supply chain.
- *Application* is concerned with the type of problem-solving task for which the ontology is to be used. These tasks span a wide range of applications along the life-cycle of a supply chain (e.g., design, planning, and control).
- *Size* is concerned with the number of concepts, relationships and axioms that constitute the ontology. Retrieving this information depends on the availability of either a formal specification or sufficient details described in the respective articles. If these are incomplete or missing, we will give a lower bound of each number, if possible at all.
- *Key concepts* is concerned with the top-level concepts that are central to each ontology. We will list at least six key concepts to provide some indication of the focus of each ontology. It must noted, though, that a deeper content analysis of SCM ontology would require much more effort and also resolve terminological differences, which are out of scope of our survey.

3.3 Identified Supply Chain Ontologies

The search process yields 16 ontologies. Since few ontologies have a distinct name, we will refer to each ontology by the respective publication. Table 2 lists these ontologies in chronological order and shows the values for the criteria users, scope, and application.

Table 2. Users, Scope, and Application of Identified Ontologies.

Author	Users	Scope	Application
Soares et al., 2000 [41]	Software developers	Microelectronics supply chain	Production planning and control in the semiconductor industry
Madni et al., 2001 [42]	Application systems	Supply chain	(1) Crisis action planning and execution, (2) Integrated product process development
Pawlaszczyk et al., 2004 [43]	End-users, software developers, domain experts, consultants	Mass customization supply chains	Agent-based supply chain simulation
Fayez et al., 2005 [44]	People	Supply chain	Supply chain simulation
Matheus et al., 2005 [45]	Application systems	Logistics	Monitoring of spare parts logistics
Chandra and Tumayan, 2007 [11]	Knowledge workers, software engineers, and decision makers	Supply chain	Decision support for scheduling in multi-state steel manufacturing processes
Gonnet and Vegetti, 2007 [46]	People	Supply chain	None
Leukel and Kirn, 2008 [47]	Customers and suppliers	Logistics	(1) Reconstruct supply chain from knowledge base, (2) Aggregating process fragments
Ye et al., 2008 [48]	Application systems	Supply chain	Mapping of two business document standards to the ontology
Chi, 2010 [49]	Application systems	Supply chain	Tracing of suppliers and inbound freight
Grubic et al., 2011 [50]	People	Supply chain	Modeling and quantitative analysis of supply chain processes
Sakka et al., 2011 [51]	People	Supply chain	Transforming SCOR models
Zdravkovic et al., 2011 [12]	People	Supply chain	Designing visual supply chain models
Anand et al., 2012 [38]	Software developers, application systems	City logistics	Automated categorization, query answering, modeling and simulation
Scheuermann and Hoxha, 2012 [52]	Service-oriented application systems	Logistics	Logistics vocabulary, interoperability and integration
Lu et al., 2013 [39]	Application systems	Supply chain	Integrating product information into supply chain

Users are equally segmented into design-time and run-time, with only one ontology addressing both [38]. Whereas five publications very generally state "people" as users, we found more specific groups of people involved in systems design in other publications.

Ten ontologies are concerned with supply chain in the broadest sense, and two ontologies restrict the scope to specific types of supply chain. Logistics and SCM are closely related terms, though the literature still provides different interpretations for both as well as for their differentiation. We follow the perception that SCM is a broader concept with regard to its tasks and objectives; this interpretation is appropriate to classify all three logistics ontologies accordingly.

The range of applications is rather wide, spanning support of diverse tasks such as modeling, planning, scheduling, simulation, and information integration. These tasks correlate with the addressed groups of users, e.g., end-users perform simulation experiments, or application systems create production plans.

Table 3 lists the results for criteria ontology size and key concepts. The majority of ontologies is rather small, with only three ontologies exceeding 100 concepts and relationships. Retrieving the actual size exactly or giving an approximation was made difficult by the form of documentation and ontology delivery, which often provides only a snapshot of the entire ontology or unspecified 'blank' relationships. The ontologies proposed by Zdravkovic et al. [12] and Sakka et al. [51] are formal specifications of a reference model from industry but give no clear information about the ontology's coverage of this model, thus it was not possible to deduce the number of concepts and relationships contained in the ontology.

The ontologies provide varying key concepts that range between six and 12. These concepts incorporate different levels of domain and specificity (e.g., process, resource, and objective vs. logistics service, logistics resource, and logistics KPI). The granularity of the ontologies in terms of a strategic, tactical, or operational focus cannot be determined unambiguously.

4 Analysis of SCM Ontologies

This section presents the review results. We refer to the model of ontology engineering (constructs, measurements) that was discussed in section 2. For each measurement, we check if the publication contains a statement or indication about how the measurement materializes in the ontology, respectively the reported development process. If no reference is found, we code the measurement as "not reported". Due to the wide time range (2000 to 2013), not all measurements are applicable to all ontologies. Ontology design patterns were proposed in 2005 [34]. The World Wide Consortium (W3C) recommended OWL in late 2004, thus after the publication date of at least three ontologies. In this case, we mark the measurement as not applicable (N/A). Next, we will present the results for each of the six constructs. Table 4 summarizes the coding for the first three constructs, while Table 5 provides the results for the latter three constructs.

Table 3. Size and Key Concepts of Identified Ontologies.

Author	Size			Key Concepts
	#concepts	#relationships	#axioms	
Soares et al., 2000 [41]	45	N/A	N/A	Organizational Unit, Plan, Resource, Order, Product, Activity
Madni et al., 2001 [42]	28	46	N/A	Enterprise, Process, Resource, Objective, Plan, Activity
Pawlaszczyk et al., 2004 [43]	118	13	N/A	Activity, Plan, Product, Organization, Time, Event, Transfer-Object, Flow, Performance
Fayez et al., 2005 [44]	>34	N/A	N/A	Functional Units, Processes, Materials, Objects, Information, Information Resources, Schemas, Performance Measures, Practices, Resources, Decisions, Views, Tiers
Matheus et al., 2005 [45]	>11	>14	N/A	Airbases, Aircraft, Parts, Facilities, Remote Supply Depots, Event Object Attribute
Chandra and Tumayan, 2007 [11]	>21	>20	N/A	Agent, Input, Output, Environment, Objectives, Functions, Processes, Products
Gonnet and Vegetti, 2007 [46]	69	90	N/A	Organizational Unit, Process, Resource, Plan, Source, Make, Deliver, Return, Enable
Leukel and Kirn, 2008 [47]	>42	>44	N/A	Process, Process Type, Good, Company, Metric, Best Practice, Information
Ye et al., 2008 [48]	>43	>22	N/A	Party, Role, Purpose, Activity, Resource, Transfer_Object, Objective, Performance, Performance_Metric
Chi, 2010 [49]	16	38	N/A	Enterprise, Product, Product Type, Selection Criteria, Location, Competence, TechLevel
Grubic et al., 2011 [50]	62	N/A	N/A	Asset, Coordination, Location, Metric, Process/Activity, Buyer, Flow, Person, Supplier, System
Sakka et al., 2011 [51]	>8	N/A	N/A	Top Level, Configuration Level, Process Category Level, SCOR Performance Attributes, Input/Output, Best Practices, Model Legends
Zdravkovic et al., 2011 [12]	>6	N/A	N/A	Actor, Input, Output, Process Element, Performance Attribute, Process Type
Anand et al., 2012 [38]	263	108	1,845	Stakeholders, Objectives, KPI, Resources, Measures, Activity, R&D
Scheuermann and Hoxha, 2012 [52]	18	19	N/A	Logistics Actor, Logistics Role, Logistics Service, Logistics Object, Logistics KPI, Logistics Resource, Logistics Location
Lu et al., 2013 [39]	N/A	N/A	N/A	ProcessCategory, ProcessElement, ProcessType, BestPractice, Feature, InputEntity, OutputEntity, Metric, PerformanceAttribute

Table 4. Methodology, Knowledge Acquisition, and Design.

Authors	OE Metho-dology	Knowledge Acquisition		Ontology Design		
		Knowledge Source	KA Technique	Principles	Patterns	Reuse
Soares et al., 2000 [41]	Uschold and King [1995]	Not reported	Not reported	Not reported	N/A	Enterprise Ontology, Plan Ontology
Madni et al., 2001 [42]	Not reported	Not reported	Not reported	Neutrality, extensibility, complementarity, interoperability	N/A	Not reported
Pawlaszczyk et al., 2004 [43]	Custom	SCOR	Document analysis	Not reported	N/A	Enterprise Ontology
Fayez et al., 2005 [44]	Custom	SCOR	Document analysis	Not reported	N/A	Not reported
Matheus et al., 2005 [45]	Custom	Not reported	Not reported	Not reported	N/A	Not reported
Chandra and Tumayan, 2007 [11]	Custom	Not reported	Not reported	Not reported	Not reported	Not reported
Gonnet and Vegetti, 2007 [46]	Gruninger and Fox [1995]	SCOR ANSI/ISA 95	Document analysis	Not reported	Not reported	Not reported
Leukel and Kirn, 2008 [47]	Custom	SCOR	Document analysis	Not reported	Not reported	Not reported
Ye et al., 2008 [48]	Uschold and King [1995]	SCOR, logistics literature	Document analysis	Not reported	Not reported	Enterprise Ontology
Chi, 2010 [49]	Custom	Experts, case studies, literature	Interview, document analysis	Not reported	Not reported	Not reported
Grubic et al., 2011 [50]	Noy and McGuiness [2001]	SCOR, GSCF	Automatic term extraction, manual synthesis	Not reported	Not reported	Checked, but no reuse
Sakka et al., 2011 [51]	Custom	SCOR	Document analysis	Not reported	Not reported	Not reported
Zdravkovic et al., 2011 [12]	Custom	SCOR	Document analysis	Not reported	Not reported	TOVE
Anand et al., 2012 [38]	Uschold and Gruninger [1996]	Not reported	Not reported	Not reported	Not reported	Not reported
Scheuermann and Hoxha, 2012 [52]	Uschold and Gruninger [1996]	Literature, standards, domain experts	Workshop, document analysis, interview	Modularization, reusability, extensibility, maintainability	Not reported	Various
Lu et al., 2013 [39]	Custom	SCOR	Document analysis	Not reported	Not reported	SCOR-KOS, ONTO-PDM

4.1 OE Methodology

All 16 publications report on ontology new development; thus, we did not find instances of reengineering, merging, alignment, and learning. The authors of six publications state that they adopted a specific method, i.e., process model. These methods stem from the mid 1990s or early 2000s and have been widely applied in ontology developments projects [53],[54],[55],[56]. Each method defines a straightforward development process that consists of activities, roles, and products. Nine publications do not report the use of such a pertinent method, but describe a custom process model; these models may have been influenced by one of the extant methods though. All these custom process models are more coarse-grained and less complex than those found in the standard methods. Only one ontology proposal does not provide any information about the development process [42]; this finding, however, could be explained by the fact that the article appears in an outlet that mainly serves a practitioner's readership, which might pay less attention to the use of specific OE techniques.

4.2 Knowledge Acquisition

The most frequently used knowledge source is the Supply Chain Operations Reference Model (SCOR) [57], which was found in nine publications. Being a process reference model, SCOR is actively promoted by a stellar group of firms from various industries, and thus has become a widespread modeling technique for supply chain design. In addition, SCM research makes use of SCOR for designing both descriptive and analytical methods for various supply chain problems. As such, it provides a common terminology, a comprehensive set of supply chain processes, and performance metrics. The adoption of SCOR by SCM ontologies is diverse. For instance, Sakka et al. [51] as well as Gonnet and Vegetti [46] only borrow some core concepts such as Make, Deliver, Source, Plan, Execute and Enable and then integrate these concepts into a custom conceptualization. As opposed to that, both Leukel and Kirn [47] and Zdravkovic et al. [12] deduce their proposed ontology from a rigor subset of SCOR; this form of deduction is also referred to as "ontologizing". Apart from SCOR, the authors of three ontologies explicitly state that the literature from SCM, logistics, or operations management was considered as knowledge sources. Surprisingly, only two publications note that domain experts were participating in the knowledge acquisition activity.

The choice of knowledge acquisition techniques depends very much on the type of knowledge source. Therefore, document analysis is the primary technique for retrieving knowledge from specifications such as SCOR (interview and workshop for domain experts). Grubic et al. [50] briefly describe the process of automatically extracting terms from textual specifications and using these terms as candidates for concepts. If we assume that the width and depth of the SCM field mirrors in a variety of different types of knowledge sources, then we must note that only two out of 16 publications report the combination of two or more knowledge acquisition techniques to appropriately deal with this variety [49],[52].

4.3 Ontology Design

As can be seen from Table 4, 14 out of 16 publications have no discernible design principles present. A possible explanation is the universal validity of principles that are applicable to many design tasks; similar principles can also be found in the literature on conceptual modeling and software design, though terminology and coverage are partly different. The adoption of ontology patterns was neither found nor could be traced backed from studying the semi-formal and formal specifications (to the extent possible). For the third measurement, the level of adoption is much higher: Six ontologies reuse the following existing formal ontologies: Enterprise Ontology [58] and TOVE [59] are concerned with singles firm and intra-organizational integration; SCOR-KOS is a subset of the ontology proposed by [12]; ONTO-PDM is a product ontology [60]; and three other ontologies for units of measurement , hazardous cargo, and airline codes [52]. In one case, existing ontologies were assessed but disregarded for reuse [50].

Table 5. Specification, Evaluation and Delivery.

Authors	**Ontology Specification**		**Ontology Evaluation**	**Ontology Delivery**	
	Language	**KR Paradigm**		**Documen-tation**	**Availa-bility**
Soares et al., 2000 [41]	Thesaurus, UML class diagram	Algebra of sets	Not reported	Article	Not reported
Madni et al., 2001 [42]	UML class diagram	Algebra of sets	Application	Article	Not reported
Pawlaszczyk et al., 2004 [43]	Frames	F-Logic	Not reported	Conference Proceedings	Not reported
Fayez et al., 2005 [44]	OWL	DL	Not reported	Conference Proceedings	Not reported
Matheus et al., 2005 [45]	OWL, SWRL	DL	Application	Conference Proceedings	Not reported
Chandra and Tumayan, 2007 [11]	Algebra, XML Schema	Algebra of sets	Scenario	Article	Not reported
Gonnet and Vegetti, 2007 [46]	OWL (UML)	DL	Scenario	Book Chapter	Not reported
Leukel and Kirn, 2008 [47]	OWL	DL	Scenario	Conference Proceedings	Not reported
Ye et al., 2008 [48]	OWL	DL	Scenario	Article	Not reported
Chi, 2010 [49]	OWL, SWRL	DL	Case study	Article	Not reported
Grubic et al., 2011 [50]	Frames	F-Logic	(1) 3 case studies, (2) scenario	Article	Not reported
Sakka et al., 2011 [51]	OWL	DL	Scenario	Article	Not reported
Zdravkovic et al., 2011 [12]	OWL	DL	Scenario	Article	Not reported
Anand et al., 2012 [38]	OWL	DL	(1) Informed argument, (2) 2 case studies	Article	Not reported
Scheuermann and Hoxha, 2012 [52]	OWL	DL	(1) Experiment, (2) scenario	Conference Proceedings	Not reported
Lu et al., 2013 [39]	OWL, SWRL	DL	Scenario	Article	Not reported

4.4 Ontology Specification

Our analysis suggests that OWL is the standard ontology language for SCM ontologies: Once OWL became a W3C Recommendation, all but two ontologies [11],[50] use OWL. This language is actually a family of three sub-languages (in OWL 1.0/1.1) respectively profiles (in OWL 2.0), which provide different expressivity. In our analysis, however, we could not find any evidence for using sub-languages or profiles. Three ontologies complement the specification with rules that process ontology instances [49],[39],[45]; these rules are being described using the Semantic Web Rule Language (SWRL), which is still a W3C member submission. Gonnet and Vegetti [46] illustrate the ontology's structure by means of UML class diagrams; the reason is that OWL lacks a standard graphical notation. Therefore, ontology engineers must often either rely on notations that are implemented in particular OWL editors, or employ notations that are not specifically made for ontology. Due to the diffusion of OWL, description logic was found as the dominating KR paradigm.

4.5 Ontology Evaluation

Three of the very early ontology proposals supply no specific information to demonstrate the ontology's utility, but merely provide claims about this important property. With regard to syntactic quality, no publication elaborates on this dimension; this observation can be attributed to the assumption that any ontology must be syntactically correct; in addition, ontology engineering tools provide means for guaranteeing the syntactic correctness. Therefore, the authors could have omitted reporting about its assessment.

Two proposals report about an application system that uses the ontology; however, the level of detail found in these reports is rather low, e.g., both reports lack sufficient data on the application and explicitly defined metrics. Scenario-based evaluation is the most frequent method; typically, the authors describe a supply chain setting and then show how the ontology is used to represent this setting, respectively it assists in solving a particular task. In two instances, the authors assert to provide a "case study" [11],[46], but they actually construct a scenario (abstraction, no actual firm). Therefore, semantic quality is the focal point of evaluation in nine publications. Pragmatic quality was subject in four evaluation procedures: Three papers contain case studies, which, however, do not provide quantitative data about user interpretations, but qualitative findings. One ontology was evaluated through a class-room experiment, which involved ten university students and ten practitioners from the logistics domain [52].

4.6 Ontology Delivery

The 16 ontologies are published in various application-oriented scientific outlets that mainly span journals (10) and conference proceedings (5). Surprisingly, no single ontology is supplemented by material that may assist users in implementing the ontology (e.g., user's manual, web page). Similarly to this finding, each ontology lacks the provision of a machine-processible specification. Only Matheus et al. [45] and Ye et al. [48] use the article's annex to make available the formal specification (in OWL DL and SWRL). Thus, the problem with most ontologies is that from reading the respective paper it is difficult to grasp the formal specification sufficiently. Very often, the level of description is rather high and thus lacks details that cannot be taken from the graphical illustration (modeling scripts such as class diagrams), verbal descriptions, and code fragments.

5 Discussion

In this section, we discuss the findings by revisiting each construct of the research model and draw implications from our review.

5.1 OE Methodology

Our analysis indicates that ontology developers acknowledge the importance of OE methodology. In contrast to this, an earlier study among developers reported (1) that 60% do not use any method and (2) a much greater spectrum of specific methods for the remaining 40% of respondents [17]. While our observation is encouraging, we did not find specific reasoning on how to select an appropriate method for the SCM domain. It was our expectation that the domain's diversity of stakeholders and multiplicity of theoretical perspectives mirrors in domain-specific characteristics, e.g., placing greater emphasis on collaborative knowledge acquisition techniques that integrate these stakeholders and perspectives, as well as procedures for resolving conflicting and integrating overlapping conceptualizations. Thus, we suggest future research to study the applicability of collaborative OE methods [61], [62] to the SCM domain, and assess its utility compared to standard methods. This avenue of research could help answering the following question:

Research Question 1: How to design collaborative OE methods effectively for SCM ontology?

5.2 Knowledge Acquisition

We observe that very few ontologies are grounded on specific SCM frameworks, conceptual models, or theories. A similar finding was reported in the study by Grubic and Fan [15] (denoted as Gap 9). Thus, the rich archival knowledge of SCM has been widely ignored by the ontology developers; at least, the publications fail to make the deduction visible to the reader.

An important observation is the dominance of SCOR as an authoritative source of knowledge. Whereas the SCM literature also suggests the relevance of SCOR, we found different degrees of adoption as well as various knowledge acquisition techniques; these degrees range from inspiration to strict deduction that maintains the original conceptualization and terminology of SCOR. However, all respective publications provide very few details about the acquisition process, if problems occurred, and what measures the developers implemented to guarantee that the ontology correctly reflects the SCOR model. The difficulty with SCOR is that it lacks a formal specification, but is described by a handbook that is targeted for the business audience. Thus, deducing the conceptualization is not trivial, but requires domain expertise and is also in danger of interpreting the documentation falsely. These problems are caused by the nature of the documentation (semi-structured, serving domain experts) and therefore could exist for other domain models as well. We recommend that future research rigorously applies acquisition methods for these knowledge source by increasing the involvement of domain experts, assessing the level of mutual interpretation of these sources through measures for inter-coder reliability, and explicitly denoting those parts of the ontology that were deduced from a domain source.

5.3 Ontology Design

Unlike business process design [63] and software architecture modeling [64], the idea of patterns has yet not received appreciation by SCM ontologies. However, OE researchers undertake remarkable efforts to creating design patterns and providing them in catalogues that contain both comprehensive documentation and formal specification (OWL code fragments). Considering the gap between extant patterns and their adoption, we advocate a shift from inventing novel ontology patterns (design science research) towards studying the practical use and potential utility of these patterns in realistic SCM contexts that involve subjects of SCM stakeholders (behavioral research):

Research Question 2: What design patterns are most effective for SCM ontology?

Ontology reuse depends foremost on the availability of high-quality ontologies that can easily be integrated into the overarching SCM ontology. We found fulfillment of this constraint for firm-level ontologies, i.e., the Enterprise Ontology and TOVE. Current research takes these popular ontologies for granted. What we would expect is that the concepts of any firm-level ontology can be traced backed or mapped to constructs of relevant firm-level theories. In this way, either the firm-level and supply chain-level ontology would reflect findings from the domains that they conceptualize. Concerning the firm-level, IS research makes a specific contribution in form of the so called *Bunge-Wand-Weber ontology* (BWW ontology) [65], which is widely studied in the conceptual modeling field. Unfortunately, the BWW ontology is still not available in OWL. We suppose that the BWW ontology could also serve as top-level ontology and thus provide some kernel concepts for SCM ontology, and suggest future research to explore the links between this ontology and supply chain. In addition, Wand and Weber provide a representational model for assessing the effectiveness of models (i.e., by measures for construct redundancy, overload, deficit, and excess):

Research Question 3: What top-level ontology is most effective for reuse by SCM ontology?

5.4 Ontology Specification

Based on the sample of SCM ontologies reviewed, OWL is the most popular ontology language. This finding, however, was expected, since it reflects the historical development, which first had led to various proposals and then saw a concentration on the W3C's standard language. At the same time, the maturity of OWL-based editors, reasoners, query languages, and storages as well as adoption by industry increased greatly. Closer examination revealed that no publication discusses OWL profiles, thus does not elaborate on the ontology's expressiveness that must be covered by the language used. Expressiveness is an important property of ontology, since it affects the underlying semantic infrastructure. Despite this importance, the literature does not inform us on level of expressiveness is required for SCM ontology. More specifically, it is yet not known which SCM constructs necessitate the use of particular OWL constructs. For instance, OWL was extended in its current version 2 by constructs for qualified cardinality restrictions, property chains, and keys. Whether these advanced constructs are helpful for SCM ontology is unclear. Most current ontologies, however, do not exploit the expressivity of OWL but are confined to defining class hierarchies (taxonomies), few relationships, and thus addressing terminological problems. This observation reinforces a finding reported in the study by Grubic and Fan [15] (denoted as Gap 8 and 9). Therefore, we argue that future research should study the relationship between SCM domain constructs and ontology language constructs. Advancing our understanding in this regard could also be useful for choosing respectively designing the appropriate semantic infrastructure for ontology-based SCM applications. We address this research gap by the following research question:

Research Question 4: What ontology language constructs and expressivity are required by SCM ontology?

5.5 Ontology Evaluation

Our review shows that most researchers tend to demonstrate the utility of SCM ontology by means of descriptive evaluation methods, i.e., constructing detailed, though rather small-scale scenarios, or reporting on applications that use the ontology. What is missing are well-defined evaluation metrics that measure semantic and pragmatic quality. Notable is the paucity of user experiences and user perceptions in carrying out the evaluation. From a methodological perspective, our findings suggest that ontology evaluation in current SCM ontology research is in an early stage and poorly treated. Since evaluation is an essential task within the research process, we contend that future research on SCM ontology should more carefully select and apply rigorous evaluation methods. Although the maturity of these methods for syntactic and semantic quality progressed in OE research, researchers should also be informed by empirical evaluation methods that are being used in conceptual modeling research. We believe that this field can contribute well-defined evaluation metrics, guidelines for experimentation and data analysis as well as a stronger theoretical underpinning of the overall evaluation approach and procedure [66],[67], and thus addresses the pragmatic quality gap that we articulate as follows:

> *Research Question 5: What empirical evaluation methods and metrics are most effective for demonstrating the pragmatic quality of SCM ontology?*

5.6 Ontology Delivery

None of the 16 ontologies is available on the Web or can be fully retrieved from reading the publication. This finding was not anticipated given the fact that ontology research was greatly propelled by the Semantic Web vision [68]; it postulates that ontologies will (1) form the backbone of this extension of the current Web and (2) become public, reusable, and inter-linked conceptualizations. While it is often stressed that we are still far away from such a Web [17], our finding has an immediate implication for conducting research: The absence of any accessible SCM ontology prevents other researchers to reuse, extend, integrate, and evaluate these IT artifacts. As a consequence, the consistency, soundness, and – most importantly – utility of these ontologies have not been fully tested. To overcome this shortage, we argue that researchers should disseminate their SCM ontologies into the communities via ontology libraries, which are specifically designed for a wider audience [69].

6 Conclusion

This article provides an in-depth review of the existing literature on SCM ontology. To assess the extent of linkages between OE techniques and this type of ontology, a systematic process was used to classify the literature along salient OE constructs. We identified 16 SCM ontologies, which we analyzed for six constructs and 14 measurements. The review enables us to succinctly describe the proposed ontologies, assess their adoption of OE techniques, and outline an agenda for future research by articulating five specific research questions. We found a relative low, though increasing, degree of adoption of OE techniques. In particular, few proposals (1) reuse existing conceptualizations, thus draw little from the SCM literature and previous efforts for ontology development, (2) exploit the expressiveness of ontology languages, and (3) demonstrate the ontology's utility by thorough metrics and through well-executed evaluation methods. These findings are similar to those reported in a prior survey of task ontologies for supply chain planning [21], though SCM ontology is of broader scope and also a more active research area. The identified methodological shortcomings could be mitigated by at least two advancements. First, we suggest aggravating empirical research that evaluates OE artifacts in SCM settings. Second, endeavors to SCM ontology should be more informed by the conceptual modeling literature, which might strengthen the theoretical foundation of OE in an organizational context.

The review is limited in several ways. First, the survey may be incomplete due to the search process that relied on specific databases and selection criteria for quality. Second, due to the absence of an original OE theory, the research model must be constructed from the literature, and thus might be incomplete or lack supporting empirical evidence. Third, since no ontology supplies a machine-readable formal specification, we could neither inspect the ontologies by applying formal analysis techniques nor assess the proposed conceptualizations in great detail. Instead, it was necessary to restrict the analysis to studying the publications for instances of all the constructs, respectively measurements. Once SCM ontologies become available on the Web, researchers will be able to directly using these artifacts for conducting experimental and empirical research.

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