Task Ontology for Supply Chain Planning – A Literature Review

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Abstract. In recent years, ontology has been proposed as a means for formally specifying the planning tasks within supply chain management. The literature yields a variety of such ontologies and reports their use for diverse settings of supply chain planning. However, the methodological foundation of these ontologies is still subject of inquiry. In particular, it is still unclear to which extent the efforts carried out for developing these ontologies have made use of the constructs, insights and methodologies from the knowledge engineering discipline. This article presents a study of state-of-the-art research on task ontologies for supply chain planning by reviewing the most relevant plan ontologies and assessing their methodological foundation and maturity. The implications for prospective ontology users are discussed and future research on ontologies for supply chain planning articulated through specific research questions.

Keywords: expert systems; supply chain management; literature review; ontology

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1. Introduction

Supply chain planning is a critical business problem. With the increasing global division of labour, the performance of a single company depends more and more on its ability to maintain effective and efficient relationships with its suppliers and customers. Planning tasks are moving from an organisational scale to a supply chain scale (Lambert and Cooper 2000) and thus encompass the inter-organisational integration and coordination of globally dispersed supply chain activities that are required for moving products from the downstream suppliers to the upstream customers. These tasks increasingly depend on the availability, correctness, and interpretability of the relevant knowledge as well as the ability to exploiting this knowledge for effective managerial decisions (Hult, Ketchen, and Slater 2004; Rai, Patnayakuni, and Seth 2006).

From a knowledge engineering perspective, ontology is a means for formally capturing domain and task knowledge. The literature yields a variety of ontologies that formally specify the planning tasks. Research suggests the usefulness and efficacy of these ontologies for diverse planning tasks, including supply chain planning. A plan ontology characterises the problem solving structure of planning, that is foremost a set of planning activities as well as actors, resources, and states. (Mizoguchi, Vanwelkenhuysen, and Ikeda 1995). The ontology is an essential component of knowledge-based systems (KBS) for supply chain planning (Singh 2003). In essence, the plan ontology describes what is reasoned about, but does not define the procedure of carrying out planning activities (planning method).

Whereas researchers apply ontology to supply chain planning, there is still little knowledge about the concrete linkages between this type of ontology and ontology engineering (OE) methodologies. In particular, it is still not known to which extent the efforts carried out for developing these ontologies have made use of the constructs, insights and techniques from the OE field. It is unclear how research on ontology for supply chain planning is informed by outcomes of the OE researchers. Over the past 20 years, the OE field has made significant advances with regard to its constructs, models, tools, and theoretical perspectives (Corcho, Fernández-López, and Gómez-Pérez 2003; Staab and Studer 2009). When examining the emergent literature on ontology for supply chain management (SCM) in general and supply chain planning in particular, it is also striking that the ties between the two fields of SCM and OE do not seem to be very strong (Grubic and Fan 2010; Ye et al. 2008). Recent empirical research has greatly enhanced the understanding of the applicability and usefulness of OE techniques (Cardoso 2007; Simperl, Mochol, and Bürger 2010), though little recognition has been given to assessing the methodological foundation and maturity of specific ontologies.

A weak methodological foundation of plan ontologies may negatively affect the quality and thus applicability of these ontologies. The problems resulting from this weakness are illustrated as follows:

Ontological commitment: Using a given plan ontology implies an unrestricted commitment to the conceptualization of this ontology. Since the ontology stems from a third-party, it is necessary to supplement the ontology with sufficient user-directed information so that users can fully grasp the intended semantics of the ontology. If the user is left alone with the formal specification, then it may be difficult for him/her to map ontology elements to his/her domain of discourse and vice-versa (e.g. when using an industry-independent plan ontology for an industry that is characterized by a high share of specific, idiosyncratic terms).

Evaluation: Evaluating plan ontologies and selecting the best suited one can be a time-consuming, tedious task that depends on many factors such as the user's domain knowledge and experience with ontologies. If detailed analysis is not reasonable, it is up to the ontology provider to supply convincing information that could support decision makers. In particular, the rationale for the conceptualization must be justified; for instance, by demonstrating what relevant knowledge sources from the SCM field have been exploited by the ontology designers and how this deduction process mirrors in the ontology. Moreover, the plan ontology could be evaluated for certain properties, e.g. by reporting about evaluation procedures such as case studies, field studies, laboratory experiments, and analytical assessments. If these are missing, prospective users may be sceptical about the ontology's quality and refrain from using it.

IT integration: Plan ontology also concerns the IT systems level; ideally, the formal specification can be directly imported into a KBS (e.g. serving as the schema of a semantic storage) or processed by another system such as converter, database management system, or supply chain modelling tool. Such processing is only possible, if a complete formal specification exists, adheres to a standard serialization and is syntactically correct.

The objective of this paper is to review and analyse current task ontologies for supply chain planning with regard to their methodological foundation. The authors report about a systematic literature review, present the findings, and discuss implications for both prospective ontology users and researchers. Therefore, this research contributes to the understanding of the ties between a particular type of ontology and OE methodologies, and by unfolding these ties suggests directions of future research.

The remainder of the paper is as follows. Section 2 describes the theoretical background to the review. Section 3 describes the review process and briefly introduces the relevant ontologies. Section 4 reports the review results. Section 5 discusses the findings and implications. Section 6 concludes the paper.

2. Theoretical Background

2.1. Ontology

In its original meaning, ontology denotes the branch of philosophy that deals with the "the science of what is, of the kinds and structures of objects, properties events, processes, and relations in every area of reality" (Smith 2003, 155). With the beginning of the 1990s, ontology became a substantial topic in Computer Science and Artificial Intelligence (AI) research. AI is concerned with the formal representation of models of real world phenomena and the reasoning about these models. Literally spoken, AI research *borrowed* the term ontology from philosophy and equipped it with a computational meaning by shaping the term "formal ontology".

Based on this understanding, Studer, Benjamins, and Fensel (1998, 185) define ontology as "a formal, explicit specification of a shared conceptualization of a domain of interest". C*onceptualization* 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, whereas *formal* indicates that the ontology should be readable and interpretable by machines; thus, formal excludes the use of natural language. At last, *shared* conceptualization reflects that a formal ontology captures consensual knowledge that is not private to an individual person but accepted by a larger group of individuals.

Ontology has spread out to many application-oriented fields and audiences (Staab and Studer 2009). SCM and more specifically supply chain planning is a particular field of application for ontology, which materialized into ontology for supply chain planning. To carve out the scope of the inquiry, it is necessary to distinguish types of ontology. The classification by Guarino (1998) provides four types of ontology:

- *Top-level ontology* is a conceptualizations being independent of a particular problem or domain; for instance, it concerns space, time, object, and event.
- *Task ontology* describes the vocabulary related to a 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* describes the vocabulary related to a domain such as healthcare, automotive, or education.
- *Application ontology* provides concepts depending both on a particular task and domain, e.g. clinical pathway, general inspection, and final exam.

Referring to this classification, ontology for supply chain planning belongs to task ontology, with supply chain planning being the task, but irrespective of a domain such as industry segment, product group, or manufacturing process.

2.2. Task Ontology for Supply Chain Planning

Task ontology for supply chain planning essentially brings together task ontology as a particular type of ontology and supply chain planning as a particular type of task. Next, these two ingredients are discussed separately prior to characterising their conjunction.

Task ontology is concerned with the problem solving structure of tasks independently from a domain. By analyzing real world problems, one can identify generic activities for performing these tasks. If the problem solving structure is described as sentences of natural language only, then the ontology must provide the vocabulary to represent these sentences formally. Thus, task ontology consists of at least three types of concepts (Mizoguchi, Vanwelkelnhuysen, and Ikdea 1995):

- *Nouns* represent objects that are created, processed, and manipulated by the problem solving process,
- *Verbs* represent activities that are part of the problem solving process, and
- *Adjectives* represent characteristics of the objects.

From the list above it is clear that task ontology provides only primitives for representing the problem solving structure but no concepts for control structures.

Supply chain planning is a task concerned with the purposeful coordination and integration of globally dispersed supply activities ranging from the procurement of raw materials to the distribution of the final products to the individual end-customers (Lambert and Cooper 2000). The problem solving process in such complex and dynamic networks of firms relies on task knowledge that captures the problem solving structure.

(Table 1) provides example concepts of supply chain planning ontology by referring to the three types of concepts. These concepts are specializations of generic task concepts.

Table 1: Example Concepts in Task Ontology and Supply Chain Planning Ontology

Type	**Task Ontology**	**Supply Chain Planning Ontology**
Nouns	“Schedule”, “Resource”, “Job”, “Due date”, “Constraint”	“Production schedule”, “Sourcing schedule”, “Delivery schedule”, “Bill-of-material”, “Customer order”, “1st tier supplier”
Verbs	“Assign”, “Remove”, “Create”, “Delay”, “Begin”, “Terminate”	“Deliver”, “Source”, “Make”, “Put on stock”, “Take from stock”, “Return”, “Transship”, “Charge”
Adjectives	“Idle”, “Busy”, “Unassigned”, “Assigned”, “First”, “Last”	“First tier”, “Second tier”, “Excess”, “Cash-to-cash cycle time”

Supply chain planning can be described by constructs that add planning-specificity to the problem solving structure: *Planning Paradigm* is concerned with the level of autonomy of different actors that are involved in the planning process: *Hierarchical planning* relies upon a central planning entity and no or little local autonomy. Planning takes place by decomposing compound tasks into more specific subtasks under consideration of a set of constraints that must be fulfilled to arrive at a valid plan (Schneeweiß and Zimmer 2004). *Non-hierarchical planning* follows a decentralised approach that allows supply chain actors to maintain their local autonomy. This planning paradigm essentially requires a positive attitude towards transparency, cooperation, and mutual trust (Dudek and Stadtler 2005).

Planning Scope describes the temporal and functional dimension of the planning problem addressed. The *temporal dimension* is measured by the time horizon, which is classified into *strategic*, *tactical*, and *operational* (i.e. long-term, medium-term, and short-term planning problems). The *functional dimension* distinguishes supply chain *structure* (e.g. planning the members, their locations and relationships) and supply chain *behaviour* (e.g. planning the flow of goods and services to fulfil customer demand) (Beamon 1998).

Industry Applications denotes the task context of the actual or intended use of the ontology for specific industries, segments, markets, or customers. It is measured by *branch of industry* and the *state of usage* (planned, laboratory, field study, real-world users).

2.3. Knowledge and Ontology Engineering

The relevant theories and constructs stem from the knowledge engineering discipline, which is concerned with knowledge-based systems. Specifically, constructs can be drawn from ontology engineering research as a field within knowledge engineering. Ontology engineering "investigates the principles, methods and tools for initiating, developing, and maintaining ontologies" (Sure, Staab, and Studer 2009, 135). The basic premise is that OE as a collective, non-observable construct positively affects the quality of the produced ontology (Gómez-Pérez, Fernández-López, and Corcho 2004). Through this quality, OE indirectly contributes to the problem solving performance (ontology is a component of the problem solving system). However, the quality of an ontology is a complex, multi-facet property. Its assessment is often difficult, costly, or objectively not feasible at all (Burton-Jones et al. 2005). Therefore, the supposed positive effect of OE can be narrowed to user perceptions, which are represented by the *Perceived Usefulness of Ontology (PUO)* construct. The core constructs are formalised into a conceptual model, which will guide the review. The model shown in (Figure 1) contains six independent variables that represent observable constructs of OE. These constructs positively affect the dependent variable PUO, which ultimately contributes to the problem solving performance.

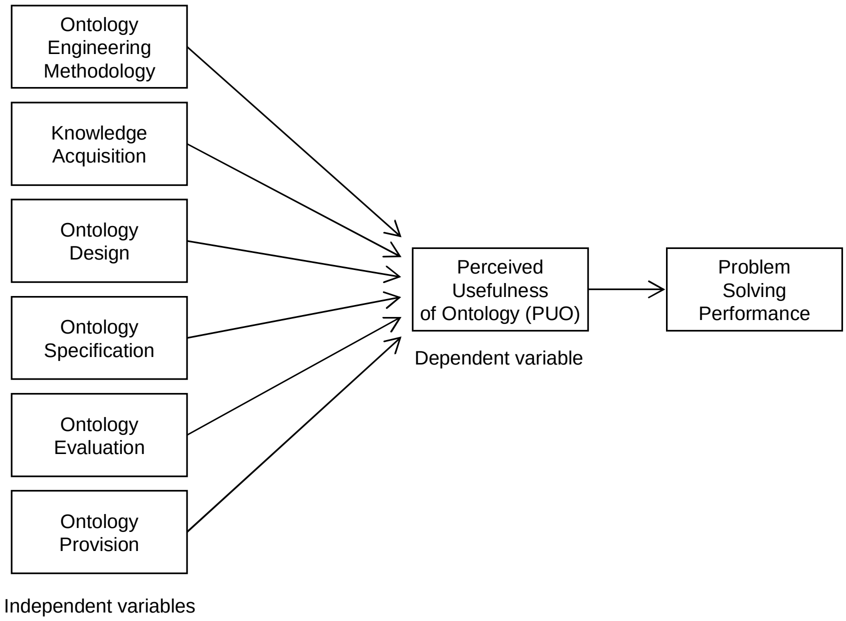

Figure 1. Conceptual Model of Ontology Engineering

Next, each independent construct and its measurements are briefly described. These constructs and measurements serve as a blueprint for the literature review and analysis.

2.4. Constructs and Measurements

2.4.1 OE Methodology

OE research brought to light numerous methodologies for constructing ontologies. These methodologies define a structured process for planning and executing the engineering of ontologies. They include approaches for either *building ontologies from scratch*, *reengineering*, *merging* and *alignment*, or ontology *learning* (Corcho, Fernández-López, and Gómez-Pérez 2003; Gómez-Pérez, Fernández-López, and Corcho 2004). Although concrete OE methodologies may differ in their underlying rationale and process, they invariably provide a set of purposeful and systematic engineering activities to produce quality ontologies.

2.4.2 Knowledge Acquisition

Knowledge acquisition is concerned with the *knowledge sources* and the *techniques for exploiting knowledge sources*. Its objective is to identify and capture the relevant knowledge. For this purpose, various techniques such as text analysis, interviews or brainstorming can be applied to different knowledge sources, e.g. domain experts, textbooks, technical articles, or specifications. In particular, acquiring task knowledge concerns a human's problem-solving capability. Therefore, knowledge acquisition must effectively support the conversion of tacit and procedural knowledge into explicit and declarative knowledge (Gaines 1987).

2.4.3 Ontology Design

Ontology design comprises techniques that assist the engineer in defining formal knowledge models. Unlike OE methodology, these techniques are more specific and can be regarded as best practices that have been proven as useful in former engineering projects. Ontology design can be measured through (1) design principles, (2) design patterns, and (3) ontology reuse. First, *ontology design principles* such as clarity, coherence, and minimal ontological commitment (Gruber 1995) are common quality criteria in terms of desiderata, i.e. desired goals that should guide the ontology construction since none of them can be directly measured and most of them cannot be perfectly achieved. Second, *ontology design patterns* represent basic ontological building blocks that offer a practical way to address recurring issues of ontology structure, content, and representation (Gangemi 2005; Presutti and Gangemi 2008). Third, *ontology reuse* denotes the adoption of top-level or core ontologies for specific task ontologies (Guarino 1998), e.g. by asserting that a new class is subclass of a top-level ontology's class.

2.4.4 Ontology Specification

The construct of ontology specification describes (1) the degree of formal semantics of ontology, (2) the language that is used for specifying the ontology, and (3) the underlying knowledge representation (KR) paradigm. *Degree of formal semantics* relates to the richness of the internal structure of an ontology, which is also denoted as semantic spectrum. This spectrum ranges from simple, less expressive to complex, highly expressive ontologies; it is often segmented into controlled vocabulary, glossary, thesaurus, taxonomy, and actual ontology (McGuiness 2003; Uschold and Gruninger 2004).

A number of *ontology languages* exist, e.g. KIF (Knowledge Interchange Format), OCML (Operational Conceptual Modelling Language), DAML-OIL (Darpa Agent Markup Language – Ontology Inference Layer), and OWL (Web Ontology Language); these languages provide different grammar, but more importantly each language implements a specific *knowledge representation paradigm* such as First-order Logic (FOL), Frame Logic (F-logic), and Description Logic (DL). Therefore, ontology languages provide different expressivity and computational decidability (Gómez-Pérez, Fernández-López, and Corcho 2004).

2.4.5 Ontology Evaluation

Plan ontologies as engineering artefacts require a thorough evaluation to ensure high quality and allow for wide adoption. Ontology evaluation concerns the techniques used for assessing quality characteristics of ontology such as consistency, syntactic and semantic correctness, completeness, and efficacy. The diversity of these characteristics requires evaluation approaches that either apply *formal verification* techniques or study the ontology's use in *knowledge-based applications* by means of controlled experiments, case studies, field studies, or simulation with artificial or real data (Brank, Grobelnik, and Mladenic 2005; Vrandecic 2010).

2.4.6 Ontology Provision

This construct denotes the way how the ontology is provided by the engineer. It consists of two measurements: *Documentation* describes the existence and types of supplementing documents that are targeted for ontology users, who are interested in the ontology, assess its applicability, or seek for the right understanding and correct usage of the ontology. *Availability* depicts whether and through which means a machine-processible specification is provided to the user.

3. Review Process

3.1. Search for Ontologies for Supply Chain Planning

To identify relevant ontologies for supply chain planning, the authors performed a systematic, iterative search for journal articles and conference papers that report on these types of ontologies. The initial search query was defined as (“plan ontology” OR “planning ontology” OR “ontology for planning”) AND (“supply chain” OR “scm” OR “logistics” OR “manufacturing” OR “application”) to retrieve both generic plan ontologies with potential applications in SCM and those specific to supply chain planning. The former were mostly found in the AI literature, whereas the latter belong to outlets of Operations Management, Industrial Engineering, and Information Systems research.

The initial search yielded a total of 127 documents (Scopus). Due to the size of the sample, the search was performed in an iterative way by adding constraints, and then manually inspecting the articles by analyzing the abstract and skimming the content. For instance, all conceptual models that are no ontology as defined by the semantic spectrum (McGuiness 2003; Uschold and Gruninger 2004) as well as ontologies that are restricted to intra-organizational planning were excluded. The query was expanded by the related terms “data model”, “information model”, “meta model”, “semantic model”, “ontology model”, “task ontology”, “method ontology”, “application ontology” as well as task-specific terms such as “supply network”, “supply web”, “production network”, “manufacturing network”, and “configuration” (to reflect the actual use of various terms for similar concepts). In addition, citation count was used as a proxy measure to identify probable core publications. SCM ontologies that do not address planning were not considered. For example, the ontology proposed in (Grubic, Veza, and Bilic 2011) is bound to modeling and analysing supply chains by persons. The final sample includes eight publications. Each publication makes an original contribution to the field, i.e., proposes a specific and formal ontology for planning with application in SCM.

3.2. *Classification Framework*

The review criteria consist of two parts: (1) ontology engineering and (2) supply chain planning. Ontology can be classified with regard to the constructs and measurements of ontology engineering and supply chain planning. The classification framework is shown in (Table 2), which lists all constructs and measurements.

Table 2: Classification Framework

Construct	Measurement
OE Methodology	– Ontology development from scratch – Ontology reengineering – Ontology merging – Ontology alignment – Ontology learning
Knowledge Acquisition	– Knowledge acquisition technique – Knowledge source
Ontology Design	– Ontology design principles – Ontology design patterns – Ontology reuse
Ontology Specification	– Degree of formal semantics – Ontology language – Knowledge representation paradigm
Ontology Evaluation	– Formal verification – Application-based evaluation – Task-based evaluation
Ontology Provision	– Documentation – Availability
Planning Paradigm	– Hierarchical planning – Non-hierarchical planning
Planning Scope	– Temporal dimension (strategic, tactical, operational) – Functional dimension (structure, behavior)
Industry Applications	– Branch of industry – State of use

3.3. *Identified Plan Ontologies*

The search process as described in section 3.1 yields eight plan ontologies as listed in (Table 3). Citation count from Google Scholar (retrieved on March 6, 2013) serves as an indicator of significance. Next, each ontology is briefly introduced as the basis for the analysis in the succeeding section.

Table 3: Identified Plan Ontologies

Plan Ontology	Acronym	Author(s) and Year	Citation Count
Shared Planning and Activity Representation	SPAR	Tate 1998	83
Process Specification Language Ontology	PSLO	Schlenoff et al. 1999	51
Joint Forces Air Component Commander Ontology	JFACC	Valente et al. 1999	126
A PLAN semantic NET	PLANET	Gil and Blythe 2000	57
Virtual Enterprise Ontology	VEO	Soares, Azevedo, and De Sousa 2000	34
DOLCE+D&S Plan Ontology Descriptive Ontology for Linguistic and Cognitive Engineering and the Ontology of Descriptions and Situations	DDPO	Gangemi et al. 2002, 2004	705
Generic Planning Task Ontology	GPTO	Rajpathak and Motta 2004	22
Ontological Formalization of Supply Chain Operations	OFSCO	Zdravković et al. 2011	17

3.3.1 Shared Planning and Activity Representation (SPAR)

The SPAR ontology resulted from the Defense Advanced Research Projects Agency (DARPA)/Air Force Research Laboratory Planning Initiative (ARPI), which aimed at accumulating and integrating various expertise from previous DARPA sponsored research of the 1980s and 1990s. Specifically, the objective of SPAR is to provide a shared, formal representation of “past, present and possible future activity [...] and the processes that create and execute plans” (Tate 1998, 121).

3.3.2 Process Specification Language Ontology (PSLO)

The PSLO was developed at the National Institute of Standards and Technology (NIST) as a universal, formal language for all processes in the design and manufacturing life cycle (Schlenoff et al. 1999). The ontology is aimed at semantic interoperability of manufacturing applications that create, interpret, and change process-related information for planning and control.

3.3.3 Joint Forces Air Component Commander Ontology (JFACC)

The JFACC was developed within another DARPA sponsored project (Valente et al. 1999). The main difference to SPAR and PLANET is that this ontology is specifically targeted at representing military objectives and planned courses of action.

3.3.4 A PLAN Semantic NET (PLANET)

The PLANET ontology originated from a DARPA sponsored project (Gil and Blythe 2000). This ontology is concerned with plans, tasks, goals and the context of planning problems. It aims at interoperability of planning applications and is independent of any particular domain.

3.3.5 Virtual Enterprise Ontology (VEO)

The Virtual Enterprise Ontology was introduced by a trans-European project with several academic institutions and industrial companies from the microelectronics industry. VEO aims at enhancing human communication with regard to requirements identification, requirements specification, and system design of an order promise module as part of a decision-support system for production and operations planning. Its scope covers virtual enterprises, i.e. temporal alliances of manufacturing companies in the semiconductor industry.

3.3.6 DOLCE+D&S Plan Ontology (DDPO)

This specifies plans in terms of tasks, their sequencing, and the controls performed on tasks (Gangemi et al. 2002, 2004). The scope of DDPO+D&S Plan Ontology (DDPO) is not limited to a specific domain.

3.3.7 Generic Planning Task Ontology (GPTO)

This ontology was developed at KMI, Open University, as a universal planning task ontology that does not subscribe to a particular planning paradigm, domain, application, or reasoning method (Rajpathak and Motta 2004).

3.3.8 Ontological Formalization of Supply Chain Operations (OFCSO)

The Ontological Formalization of Supply Chain Operations contributes to a semantic infrastructure to improve the interoperability between information systems and to enable effective knowledge management in supply chains (Zdravković et al. 2011). Its goal is to resolve some semantic inconsistencies in the Supply Chain Operations Reference (SCOR) model (Supply Chain Council 2013). The scope of the OFSCO is not limited to a particular industry sector, due to the wide scope of the SCOR model.

4. Analysis

This section reports on the review results by employing the classification framework as discussed in section 3.2. Since the ontologies span a wide time range (1998-2009), it is not possible to check the most recent measurements for all ontologies. For instance, design patterns were first proposed by Gangemi in 2005. Similarly, OWL became a recommendation by the World Wide Web Consortium (W3C) in late 2004. However, the authors tried to identify whether one of the early ontologies implicitly implemented a measurement prior to its year of final publication.

4.1. Analysis of SPAR

SPAR merges three other plan ontologies into a comprehensive ontology. These ontologies are the <I-N-O-V-A> constraint model of plans (Tate 1996a), the Plan Ontology (Tate 1996b), and the Knowledge Representation Specification Language (KRSL) Ontology (Allen and Lehrer 1992). Whereas the merge process has not been further described, the project team adopted an iterative development, refinement, and review process, which involved a core group and three panels for user requirements, specialisation, and formalisation. The knowledge acquisition thus relied upon both former ontologies and informal expert knowledge.

The ontology is specified by means of an object-oriented meta-model; however, a machine-processible specification does not exist. The ontology's authors mention that SPAR is independent from a particular ontology language and KR paradigm.

SPAR had significant influence on subsequent work. For instance, its conceptualization was adopted by the OZONE ontology that is part of a toolkit for developing scheduling systems. Applications of OZONE are reported in (Smith and Becker 1997) and (Becker and Smith 1997).

4.2. Analysis of PSLO

The development of PSLO uses a custom methodology of five phases that includes gathering of requirements, analysis of 26 existing process representations, creation of the language, implementation of a pilot application (validation), and submission of the ontology as a candidate NIST standard. Therefore, knowledge acquisition was mainly based on existing specifications and reviews by the project team. In addition, the development was driven by a domain-specific scenario (electromechanical design and planning system), and then proceeded with expanding and adding further scenarios.

The ontology is specified in KIF, which relies on FOL. The mathematical foundation of so called core theories, in particular the situation calculus (McCarthy 1963), allows for proving theorems about PSLO and verifying its consistency. Since the PSLO was submitted for becoming a NIST standard, the rudimentary documentation and lack of a machine-processible formal specification could be misleading. In 2004, the language became an international standard (ISO 18629).

PSLO is concerned with short-term planning and simulation (operational, behavioural scope; hierarchical planning). Applications of PSLO are described for business process planning (Gruninger and Menzel 2003, 69) and manufacturing processes (Schlenoff et al. 1999).

4.3. Analysis of JFACC

JFACC draws on several other ontologies, including the air campaign planning ontology ACP-SENSUS, the air campaign objectives ontology INSPECT, other ARPI planning and scheduling ontologies, and the Process Interchange Format (PIF) ontology.. The large-scale development team adopted a custom OE methodology. Knowledge acquisition was performed on formal resources (reused ontologies) and informal expert knowledge (project team).

The ontology is specified in LOOM (MacGregor 1991), which is an early DL-based ontology language. The specification of JFACC is available on the Web. A short tutorial describes the main classes and provides an overview of the ontology's structure.

JFACC concerns the military sector and, in particular, military air campaign planning; however, the main classes are independent from this particular application.

4.4. Analysis of PLANET

The literature about PLANET does not provide how the ontology was developed but focuses on its usage for different scenarios to demonstrate its applicability and extensibility. Therefore, no particular OE methodology can be identified. PLANET reuses Allen's time relations ontology (Allen 1983) and the OZONE resource ontology (Smith, Lassila, and Becker 1996). The knowledge required for PLANET was acquired through the authors' past research and experience.

The ontology consists of 26 concepts and 37 relationships. The formal specification is limited to an overview diagram, which neither depicts all these axioms nor presupposes a particular ontology language respectively KR paradigm. For evaluation purposes, the ontology has been used in three scenarios, for which the concept coverage of the ontology is determined, i.e. the degree to which the ontology provides the required concepts.

This ontology was tested in military scenarios, though its conceptualisation is fully independent from these applications. It is concerned with operational and behaviour planning.

4.5. Analysis of VEO

The development of the VEO adopts the OE methodology proposed by Uschold and King (1995) and draws upon the Enterprise Ontology (Uschold et al. 1998) as well as specific parts of the Plan Ontology (Tate 1996b). Although Soares, Azevedo, and De Sousa (2000, 262) acknowledge the particular importance of knowledge acquisition (which is entitled ontology capture in the adopted methodology), the article does not refer to specific knowledge sources used and knowledge acquisition techniques applied.

VEO consists of three main sections, i.e. networked/extended organizations, order management, and plan management, which are described by means of natural language definitions and supplementing Unified Modeling Language (UML) class diagrams.

An application of this ontology is illustrated by reporting about a requirements analysis and specification that were carried out for the global planning functionality of an order promise module. This module generates optimized production plans, capacity tests based on independent and autonomous capacity models, and reactive actions that consider possible effects on other local units. Thus, this ontology supports hierarchical planning and both operational and behaviour planning.

4.6. Analysis of DDPO

DDPO specialises concepts and relations of two other ontologies, the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) and its extension, the

Ontology of Descriptions and Situations (D&S) (Gangemi et al. 2002, 2004). Therefore, the ontology design is determined by strict reuse, while no specific methodology and knowledge acquisition method is reported.

The ontology is specified in KIF and OWL DL, thus its KR paradigm includes both First-order Logic and Description Logic. Two case studies from the publishing industry and retail are provided to demonstrate the usefulness of the ontology (application-based evaluation); for these cases, a complete specification in OWL DL Abstract Syntax is available.

Due to the ontology's generic nature, a particular planning paradigm and scope cannot be identified.

4.7. Analysis of GPTO

The knowledge resources used for developing the GPTO mainly consist of fundamental AI work on planning and constructs from seminal articles ("by amalgamating different planning paradigms" (Rajpathak and Motta 2004, 306); though the concrete acquisition method and deduction process are not described. GPTO reuses two ontologies: The Simple Time Ontology (Allen 1983) and the Base Ontology (Heflin et al. 1999).

GPTO is specified in OCML, which is based on Frames and FOL. The specification is amended with a detailed documentation.

An application of GPTO is described in (Rajpathak et al. 2006, 823), which reports on using the ontology as part of a KBS for both intra-organisational and inter-organisational scheduling problems.

4.8. Analysis of OFSCO

The development of the OFSCO consists mainly of applying an ontology language (OWL) to an existing specification that is taken from the supply chain domain (SCOR model). The authors adopt a custom OE methodology that is governed by the principles of induction, inspiration, and synthesis as introduced by Holsapple and Joshi (2002, 43-45). Knowledge acquisition takes place by applying text analysis techniques to the SCOR handbook.

OFSCO consists of three ontologies: (1) SCOR-KOS (knowledge organization system) OWL that serves as a knowledge organization system for developing an application for browsing and visualizing SCOR; (2) SCOR-CFG (helper contextual models) OWL focuses on the configuration of supply chain processes; and (3) SCOR FULL OWL that comprises 207 classes and 18 properties for representing knowledge of supply chain operations.

OFSCO inherits many properties from the SCOR model, in particular its hierarchical planning paradigm that is not constrained to a particular planning scope. Referring to SCOR's classification of supply chains, the use of OFSCO for an *engineer-to-order* supply chain is reported in (Zdravković et al. 2012).

4.9. Summary

(Table 4) summarises the analysis results for the independent variables of OE Methodology, Knowledge Acquisition, and Ontology Design.

Table 4: OE Methodology, Ontology Design, and Knowledge Acquisition

	OE Methodology	**Knowledge Acquisition**	**Ontology Design**
SPAR	Custom	Source: Domain experts Technique: Interview, review panel	Ontology reuse: <I-N-O-V-A>, PLAN Ontology, KRSL
PSLO	Custom	Source: Manufacturing scenario Technique: Interview	Not reported
JFACC	Custom	Not reported	Ontology reuse: ACP, INSPECT, ARPI
PLANET	Not reported	Not reported	Ontology reuse: OZONE Resource Ontology, Simple Time Ontology
VEO	Uschold and King, 1995	Not reported	Ontology reuse: Enterprise Ontology, Plan Ontology
DDPO	Not reported	Not reported	Ontology reuse: DOLCE, D&S
GPTO	Not reported	Source: AI literature Technique: Text analysis	Ontology reuse: Base Ontology, Simple Time Ontology
OFSCO	Custom	Source: SCOR Technique: Text analysis	Not reported

In addition, (Table 5) depicts the analysis results for the independent variables of Ontology Specification, Ontology Evaluation, and Ontology Provision.

Table 5: Ontology Specification, Ontology Evaluation, and Ontology Provision

	Ontology Specification	**Ontology Evaluation**	**Ontology Provision**
SPAR	Language: UML Object Model KR paradigm: Object-oriented	Not reported	Documentation: Article
PSLO	Language: KIF KR paradigm: FOL	Verification	Documentation: Article
JFACC	Language: LOOM KR paradigm: DL	Not reported	Documentation: Article
PLANET	Incomplete specification	Scenario-based	Documentation: Proceedings
VEO	Language: UML Class Diagram KR paradigm: Object-oriented	Scenario-based	Documentation: Article
DDPO	Language: KIF, OWL-DL KR paradigm: FOL, DL	Two case studies	Documentation: Technical report, Proceedings
GPTO	Language: OCML KR paradigm: Frame Logic, FOL	Not reported	Documentation: Proceedings
OFSCO	Language: OWL KR Paradigm: DL	Scenario-based	Documentation: Article

At last, (Table 6) presents a summary with regard to the SCM review criteria.

Table 6: Planning Paradigm, Planning Scope, and Industry Applications

	Planning Paradigm	Planning Scope	Industry Applications
SPAR	Not reported	Not reported	Not reported
PSLO	Hierarchical	Temporal: Operational Functional: Behaviour	Simulation of manufacturing processes
JFACC	Hierarchical	Temporal: Operational Functional: Behaviour	Process planning (military scenario)
PLANET	Hierarchical	Temporal: Operational Functional: Behaviour	Process planning (three military scenarios)
VEO	Hierarchical	Temporal: Operational Functional: Behaviour	Production planning and control in the semiconductor industry
DDPO	Not reported	Not reported	Not reported
GPTO	Not reported	Not reported	Scheduling
OFSCO	Hierarchical	Temporal: strategic, tactical, operational Functional: structure, behavior	Semantic interoperability in an engineer-to-order supply chain

5. Implications

This section discusses the findings and implications of the review. The results reported in the preceding section, in particular in Table 4 through 6, indicate a gap between the theory of ontology engineering and theory-testing. Next, this general assertion is backed up with more specific observations of the constructs to draw theoretical and managerial implications.

5.1. Implications for Research

5.1.1 OE Methodology

Most research on OE methodologies aims at transforming OE from an art into an engineering discipline. A survey of OE practices (Cardoso 2007) reports that 60.0% of all respondents do not use any methodology. Similarly, the review shows that plan ontologies use methodologies scarcely or not at all. This observation may suggest that OE methodologies are too complex to apply or less useful for plan ontologies. Whereas such reasons may be diverse and difficult to assess, future research might pay more attention to the effectiveness of OE for particular types of ontologies. The ontology development process has not yet been harmonized as much as other engineering tasks, in particular when compared to object-oriented software engineering, which can rely on practical, standardized but customizable methodologies, e.g. (Kruchten 2004). Thus, it is reasonable to argue for empirical research on the effectiveness of OE methodologies:

Research Question 1: Which OE methodology is most effective for plan ontologies?

5.1.2 Knowledge Acquisition

The review shows diversity of knowledge sources, which stem from AI, operations management, and SCM. No work describes the concrete steps taken to deduce ontology components from these sources, with interview and text analysis being the major techniques. Making the deduction from existing knowledge sources more transparent would (1) enable ontology users to trace back the conceptualization as well as (2) provide a stronger rationale for the conceptualization, e.g. by referring to industry standards, other foundational ontologies, or theory that is relevant to supply chain planning. This line of argumentation advocates research to address the following research questions:

Research Question 2: Which knowledge sources are most effective for plan ontologies?

Research Question 3: How to deduce knowledge from sources for plan ontologies?

5.1.3 Ontology Design

At the very beginning, design principles were an inherent part of ontological engineering. However, with the time passing by there is a trend that these principles become increasingly sidelined in OE practice. It remains rather vague how these principles may contribute to the quality of plan ontologies.

In a similar way, design patterns have not yet been fully employed for plan ontologies. This observation is in stark contrast to the role of patterns in related engineering tasks such as software design (Christopher et al. 1977) and business process design (van der Aalst et al. 2003). Therefore, research is now needed that moves from the invention of new ontology patterns (design science research) to the study of these patterns for specific OE tasks (empirical research); this shift is articulated as follows:

Research Question 4: What design patterns are most effective for plan ontologies?

Since OE is a complex, often cumbersome, and potentially error-prone engineering task, ontology reuse gains momentum on the Web. The findings provide evidence for the significance of ontology reuse, which was found in six out of eight plan ontologies. However, there is still no universal ontology that could serve as a source of formal knowledge for plan ontology (i.e. no such ontology was reused by more than one plan ontology). Therefore, additional effort is required for studying the effectiveness of ontologies to be reused:

Research Question 5: What top-level ontologies and task/domain ontologies are most effective for reuse by plan ontologies?

5.1.4 Ontology Specification

Literature argues that the selection of an ontology language is mainly determined by its computational properties in terms of expressiveness and decidability. However, the use of ontology languages and their underpinning KR paradigms by plan ontologies appears to be mostly affected by the historical development of KR (e.g. frames in the 80s/90s, description logic since it became prominent in form of OWL) as well as specific research groups that favour particular languages (e.g. OCML). This correlation is supported by two studies on the adoption of ontology languages. In 2002, Gómez-Pérez and Corcho (2002) considered the ontology languages XOL, Simple HTML Ontology Extensions (SHOE), OML, Resource Description Framework Schema (RDF(S)), and DAML+OIL as the most promising languages for the Semantic Web. In 2007, a survey revealed that particularly XOL, SHOE, and OML have a very low adoption by ontology engineers, whereas OWL, with its close ties to RDF(S) and DAML+OIL and being a recommendation of the W3C since 2004, accounts for the highest adoption rate (Cardoso 2007). Being aware of the many factors that may affect the adoption of an ontology language, knowledge about the effectiveness of these languages for plan ontologies is still limited. A recent study of manufacturing ontologies (Chungoora, Canciglieri Jr., and Young 2010) suggests that different approaches to ontological expressiveness, i.e. lightweight and heavyweight approaches result in a number of important benefits and drawbacks for using these ontologies. This knowledge could be enhanced by future research as follows:

Research Question 6: What ontology languages and KR paradigms are most effective for plan ontologies?

5.1.5 Ontology Evaluation

Research on ontology evaluation proposes various techniques to assess the quality of ontologies. The literature argues that ontologies as complex engineering artefacts necessarily require a thorough evaluation. However, current plan ontologies scarcely apply rigorous evaluation techniques, with scenario and case study being the dominating techniques. Notable is the paucity of user experiences and user perceptions in carrying out the evaluation. Although the maturity of techniques for syntactic and semantic quality progressed in OE research, researchers should also be informed by empirical evaluation methods that are being used in conceptual modelling research. This field contributes well-defined evaluation metrics, guidelines for experimentation and data analysis as well as a stronger theoretical underpinning of the overall evaluation approach and procedure (Burton-Jones, Wand, and Weber 2009). The research gap for plan ontologies is articulated as follows:

Research Question 7: What empirical ontology evaluation techniques are most effective for plan ontologies?

5.1.6 Ontology Provision

No plan ontology is fully available on the Web or can be comprehensively retrieved from reading the publication. Relevant information remains with the proposers, i.e. research groups and participating firms. This practice could be due to privacy concerns. This finding was not anticipated given the fact that ontology research was greatly propelled by the Semantic Web vision. To overcome these barriers to both consecutive, incremental research and industry adoption, researchers should disseminate their plan ontologies into the communities via ontology libraries, which are specifically designed for a wider audience (d'Aquin and Noy 2012).

5.2. Implications for Practice

This study offers practitioners insight into current plan ontologies for supply chain planning. Next, four findings are revisited to submit guidance for users who seek for a plan ontology.

The study shows that levels of plan ontology exist. The first level is formed by generic plan ontologies that stem from AI research and can be regarded as ground breaking work (SPAR, DDPO, and GPTO); although these ontologies provide the core elements of what constitutes the planning task, they are independent from supply chain and have been primarily used within AI research projects. The second level provides plan ontologies specifically for interorganisational process planning (PSLO, VEO). The final level contains plan ontologies that have been developed by acquiring knowledge from supply chain sources (OFSCO). Reusing any extant ontology must consider these levels that depict the degree of generality. Typically, ontology development would select an ontology of the second level and adapt it to the application purpose. This adaption is only possible due to the generic nature of the planning task that is captured by task ontology as discussed in section 2.2.

Plan ontology has two major groups of application by distinguishing design time and run time. Design time denotes that the ontology is used for designing a supply chain or SCM software system. In this case, the users are supply chain designers, software designers, internal and external consultants, and the parties involved in the supply chain (suppliers, customers). These users regard the ontology as foremost as a shared terminology rather than a formal specification. Accordingly, the ontology must be delivered to these users in an appropriate form that can easily be understood. Current plan ontologies meet this requirement to a varying extent. For example, VEO and OFSCO are available in both visual and formal representations. Run time denotes that the ontology is actually used within a software system, i.e. instance data is annotated with respect to the ontology. This data is then processed by software systems (data exchange across applications and supply chain tiers) and made accessible for supply chain managers, e.g. user front-ends such as planning tools, management cockpits, data analysis tools. Using extant plan ontologies for these purposes is partly possible and depends on the completeness of the formal specification and its delivery in machine-readable format. As discussed in section 5.1.6, additional efforts are required for retrieving and completing the specification.

Our study supports the role of OWL as the standard ontology language. Formerly, literature advices ontology engineers to first design a conceptual model by applying a conceptual modelling language that is independent from a specific serialization (e.g. ERM, UML class diagram), and then converting the model into a formal ontology. This approach is in danger of ignoring underlying though different assumptions. For example, OWL submits to the Open World Assumption (Corcho, Fernández-López, and Gómez-Pérez 2003), which is not common to conceptual modelling but has severe effects on any reasoning. By using OWL, all development phases rely upon description logic and thus avoid these inconsistencies. However, the state of OE software tools is still not as advanced as in software engineering, e.g. no standard visual representation of OWL ontologies available. The study reveals heterogeneity of such visualizations, which could be partly overcome by using the Functional Syntax of OWL, which is an intuitive formal representation similar to English language. Reusing a given plan ontology requires in any case to import other domain ontologies, e.g. product ontology. Again, this task is made easier by the DL foundation and OWL serialization that users should adopt.

The study indicates that plan ontology is mainly some form of vocabulary, thus its level of expressiveness is rather low. In particular, the analysis found very few constraints in these ontologies. That is, neither ontology exploits the high expressivity of OWL nor allows advanced forms of reasoning on the knowledge base. This observation, however, does not contradict the purpose of supply chain planning ontology because these constraints are left to domain ontology, not task ontology. Therefore, ontology users would select a plan ontology and then enrich the ontology by adding domain-specific constraints, e.g. for handling hazardous cargo, time windows of delivery, and qualifications of staff.

Finally, it must be recapitulated that selecting, adapting and developing plan ontology for supply chain can take place completely independent from the planning methods that govern the supply chain; this independence is due to describing the problem solving structure not behaviour (Mizoguchi, Vanwelkenhuysen, and Ikeda 1995).

6. Conclusion

The objective of this paper was to review and analyse extant ontologies for supply chain planning with regard to their methodological foundation. Eight plan ontologies were analysed based on six constructs and 18 measurements from the OE field. These were complemented by three constructs and six measurements from SCM.

A literature review of ontology for supply chain planning is difficult due to the extensive background knowledge needed for studying, classifying, and comparing these ontologies with regard to a classification framework. Therefore, the first limitation of this research is the authors' knowledge in presenting a comprehensive picture of this subject. Second, the classification framework is restricted to nine key descriptive constructs of OE and SCM. This classification could be extended and detailed with respect to OE (e.g. ontology evolution, semantic richness) as well as SCM. Mapping each ontology to a "golden standard" of supply chain planning, however, was not possible because such a standard or reference ontology does not exist yet. This limitation is also partly due to the fragmentation of the body of SCM knowledge, thus could only be overcome by intensified efforts for theory building (Harland et al. 2006).

The review results support that research on plan ontologies is informed by outcomes of OE, though the extent of adoption is relatively low, with the highest adoption for ontology reuse. There is still a significant gap between the methodological advancements in the OE field and actual use of these advances in application-oriented research and development. Therefore, this research suggests future research to focus on the usefulness and efficacy of OE methodologies. Supply chain planning ontology is a well-suited example for these studies due to its low dependency on particular industries and its high relevance to practice. For this purpose, seven research questions are posited. Most of these research questions could be addressed by empirical research, which then could provide evidence for how to develop high quality plan ontologies.

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