Computers in Industry 61 (2010) 776–786

Contents lists available at ScienceDirect

Computers in Industry

journal homepage: www.elsevier.com/locate/compind

Supply chain ontology: Review, analysis and synthesis

Tonci Grubic *, Ip-Shing Fan

Manufacturing Department, School of Applied Sciences, Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK

ARTICLE INFO

Article history:
Available online 9 June 2010

Keywords:
Supply chain
Ontology
Evaluation
Information system
Interoperability

ABSTRACT

In an environment where supply chains compete against supply chains, information sharing among supply chain partners using information systems is a competitive tool. Supply chain ontology has been proposed as an important medium for attaining information systems interoperability. Ontology has its origin in philosophy, and the computing community has adopted ontology in its language. This paper presents a study of state of the art research in supply chain ontology and identifies the outstanding research gaps. Six supply chain ontology models were identified from a systematic review of literature. A seven point comparison framework was developed to consider the underlying concepts as well as application of the ontology models. The comparison results were then synthesised into nine gaps to inform future supply chain ontology research. This work is a rigorous and systematic attempt to identify and synthesise the research in supply chain ontology.

1. Introduction

Empirical studies [1–4] suggest that supply chain integration can deliver better operational and business performance. In order to exploit all the benefits associated with supply chain integration, business has to shift its practice from information hoarding to information sharing [5]. A growing number of researchers [6–13] support the idea of supply chain integration through information flow integration. Many business solutions are promoted by the IT vendors, ranging from packaged ERP solutions, best of breed supply chain software, e-business applications to web-services. In this interacting eco-system of business needs and vendor offers, information systems interoperability is of paramount importance [9,14–18].

Themistocleous et al. [19] revealed that 38 percent of companies are not replacing their legacy systems when they implement an ERP system. Following this they also found that 58 percent of companies did not succeed to integrate their ERP systems with existing legacy systems. In a similar study [20] to benchmark the benefits and barriers of application integration, they found that all of the companies included in the research are still piecing together their legacy systems with their ERP systems. Also, the majority of 163 organizations surveyed by Davenport et al. [21] are still in the implementation phase and what is more they have not found a single company that reported completion. Sprott [22] attributed this "to differences in semantics and business rules between different applications that were never intended to collaborate" (p. 66). In order for two applications to communicate and understand each other they need to have a common syntax and semantics defined [23].

ERP systems have become a standard tool to run a business [24]. Chopra and Meindl [16] argue that these systems generate true value only if they support decision making across the enterprise and its supply chain, while Themistocleous et al. [19] assert that ERP system does not provide an integrated solution, ERP just further amplifies the need for integration. Results of studies [25,26] provide evidence that ERP systems do not adequately support supply chain integration. One reason is that these systems have not been designed to address supply chain issues but to integrate an enterprise. The inherent enterprise focus is perceived by many [27–32] as the main barrier in improving information integration of a supply chain. Hence, so-called best of breed supply chain systems have been proposed to address the lack of information integration across the supply chain. Compared with ERP systems, these products promise to narrow and stretch their focus both upstream and downstream in a supply chain. Upstream this is accomplished with SCM and Supplier Relationship Management (SRM) software; and downstream with Customer Relationship Management (CRM) software. Even though there are evidences on synergies between ERP systems and the new systems [17], interoperability is still an issue [16]. Pant et al. [33] have conducted two case studies in order to develop a framework that captures the different information system implementation approaches. They concluded that challenges in integrating different systems across the supply chain are far bigger than those faced by companies trying to integrate ERP systems.

Ontology has been suggested as the means for solving this problem [34–36]. Ontology comes from the domain of philosophy

* Corresponding author. Tel.: +44 01234 750111x5264; fax: +44 01234 752159.
E-mail address: t.grubic@cranfield.ac.uk (T. Grubic).

0166-3615/$ – see front matter
doi:10.1016/j.compind.2010.05.006

and according to Angeles [37] can be defined as "that branch of philosophy which deals with the order and structure of reality in the broadest sense possible" while Bateman [38] argues that "the general programme of ontology relies on it being possible to uncover properties that could not fail to be as they are for the world to exist." (p. 931). Guarino [39] is more specific and defines philosophical ontology as "the study of organization and the nature of the world independently of the form of our knowledge about it" (p. 628). This definition is particularly interesting since it explicitly separates ontology from epistemology and hence implies independence among those two.

This paper aims to review and analyse existing supply chain ontology models in order to inform future supply chain ontology research. The next section outlines the strategy employed for the review of literature and the third section introduces the identified supply chain ontology models. Analysis of these models is conducted by designing a comparison framework in the fourth section while the analysis results are presented in the fifth section. Before we conclude the paper and present some final thoughts, the sixth section will introduce the gaps in analysed supply chain ontology models.

2. Review strategy

A systematic literature review approach proposed by Tranfield et al. [40] was used to identify the current supply chain ontology models. This approach was adopted since it promises the thoroughness, completeness and quality of the review results. It consists of three sequential stages: (1) planning the review; (2) conducting a review; and (3) reporting and dissemination. The first stage defines the aim of the review, list of keywords and databases, and inclusion and exclusion criteria, all of which provide means for the second stage or conducting the review.

The keywords used in the search of databases were: "data model", "meta model", "information model", "ontology", "ontology model", "semantic model", "logistic", "logistics", "supply chain", "supply chain management", "value chain" and "enterprise". These have been identified by the authors as relevant and were assembled in various search strings. Databases that were searched include: Proquest, ScienceDirect, EBSCO, Scopus, Compendex, INSPEC, Emerald and CSA Technology Research Database. These databases were selected because they cover the topics and areas of interest. The abstracts and titles of papers returned from the keyword search were evaluated by the type of studies (mainly conference papers, working papers and journal papers) and time frame. The papers that satisfied these criteria then had the full paper read to evaluate for inclusion.

Besides supply chain ontology models it was also decided to include the ontology models that address the issues of virtual and extended enterprises. The latter two organizational structures are sometimes used as synonyms for a supply chain and theory recognizes them as similar inter-organizational settings [41]. All ontology models that deal with any aspect of collaborative product design or development [42–47] were excluded. Only the ontology models that address the flows of materials, services and information across a supply chain were included in the review. According to Arlbjørn and Halldorsson [48] these flows represent the core of logistics discipline and therefore its basic unit of analysis. All data, information or reference models which fall into the previously stated scope [49–52] were also excluded as they do not offer the same ground needed for the subsequent analysis and synthesis.

3. Supply chain ontology models

Six supply chain ontology models were selected from the literature reviewed, namely: (1) enterprise ontology, (2) TOVE ontologies, (3) model by Soares et al., (4) IDEON ontology, (5) manufacturing system engineering ontology, and (6) model by Ye et al. Other models not selected could be read from the extensive references provided. An overview of the selected models is provided below as an introduction to their evaluation which is presented in the fifth section.

3.1. Enterprise ontology

The enterprise ontology (EO) was developed as part of the Enterprise Project at the University of Edinburgh to explore the value of ontology for enterprise modelling. A detailed overview of the EO together with the methodology employed for its construction and applications that used the ontology is in Uschold et al. [53]. The purpose of the EO is threefold: (1) enhance communication between humans; (2) provide a basis for specifying the end-user applications; and (3) support interoperability. The EO consists of five sections: (1) Meta-Ontology and Time; (2) Activity, Plan, Capability and Resource; (3) Organization; (4) Strategy; and (5) Marketing. It should be made clear that the EO does not address any aspect of a supply chain whatsoever. Although some of the concepts which form the EO (e.g. Activity, Machine, Person, etc.) are generic to many organizations, the remaining concepts address enterprise constructs (e.g. Non-Legal Ownership, Legal Ownership, Employment Contract, etc.) that are at the very high and abstract level. Nevertheless, the EO was included in the analysis because of two reasons. First, it is a pioneering work in the area of enterprise ontology; and second it provides a foundation for some of the supply chain ontology models reviewed here.

3.2. TOVE ontologies

The TOVE ontologies was developed as part of the Toronto Virtual Enterprise Project which aimed to create an enterprise infrastructure in the form of an Enterprise Model which would have an ability to deduce answers to queries about the tasks in industrial environments [54]. The tasks have been specified in great detail and include "supply chain management which extends MRP to include logistics/distribution and concurrent engineering which looks at issues of coordination of engineering design." (p. 124). A single company perspective was taken and resulted in a set of ontologies. The ontologies developed are: resource ontology [55], cost ontology [56], organization ontology [54,57], product ontology [58], activity-state-time ontology [59] and ontology for quality management [60]. Not all ontologies are relevant in the supply chain domain; hence only the resource, organization and activity-state-time ontology were included in the comparison. The resource ontology aims to capture resources in a manufacturing enterprise while the organization ontology captures structural concepts of the organization such as: goal, division, subdivision, agent, role, and resource [57]. The activity-state-time ontology represents a foundation for the ontologies and acts as a top-level ontology.

3.3. Model by Soares et al.

The ontology introduced by Soares et al. [61] was developed to improve human communication and specify system requirements for production planning and control in the virtual enterprise environment. The ontology developed was part of a trans-European project that involved multiple academic institutions and industrial companies from the semiconductor industry sector. Its concepts are presented in the form of natural language definitions and subsequently conceptualized by object models. These were grouped under three main sections: (1) networked/extended organizations, (2) plans and (3) orders management. The foundation of this ontology was the EO; more specifically the Meta-Ontology.

3.4. IDEON ontology

The IDEON ontology is introduced in Madni et al. [62]. The purpose of this ontology is to provide a foundation for designing, reinventing, managing and controlling collaborative and distributed enterprises. The ontology was developed by employing four views that aim to capture different concepts and relationships which describe an enterprise. Each of these views is represented as separate object-oriented model using the Unified Modelling Language notation. The four views are: (1) Enterprise Context View; (2) Enterprise Organizational View; (3) Process View; and (4) Resource/Product View. The aim of Enterprise Context View is to represent the interaction of an enterprise with its environment. This view consists of several concepts that deal with observing and assessing the state of an environment. The Enterprise Organizational View concerns the structure of an enterprise and deals with lower level concepts (e.g. Goal, Strategy, Objective, Process, or Person) than the Enterprise Context View. The aim of the Process View is to equip the ontology with concepts required to represent the (re)planning-execution-control cycle. The Process concept is further classified into three concepts: Planning Process, Plan and Activity. The Resource/Product View details several types of resources required for the execution of a Process.

3.5. Manufacturing system engineering ontology

The manufacturing system engineering (MSE) ontology proposed in Lin et al. [63,64] was developed to support the application of an MSE Moderator within the environment of extended/virtual enterprise. The MSE Moderator [64] "is an intelligent support application designed to facilitate and improve concurrent engineering design by enhancing the degree of awareness, cooperation and coordination among engineering team members." (p. 5100). The MSE ontology has seven top-level classes that are further detailed and classified within a hierarchy of subclasses. Only the seven top-level classes have been explained in greater detail in Refs. [63,64] and they are: (1) Project; (2) Flow; (3) Process; (4) Enterprise; (5) Extended_Enterprise; (6) Resource; and (7) Strategy. The Project class represents the Flow of physical and non-physical items during the operation of an extended/virtual enterprise. The latter are linked by Process class that represents a transformation which in turn is enabled by different resources modelled by the Resource class. The Enterprise class provides a structure for managing processes and resources by employing different items that belong to the Strategy class. The Extended_Enterprise class represents the aggregation of different Enterprise objects.

3.6. Model by Ye et al.

The last supply chain ontology model to be reviewed here was developed and proposed by Ye et al. [65]. This model aims to serve as an Interlingua by enabling the semantic integration between heterogeneous information systems in a supply chain. The supply chain setting of the proposed ontology is a web-based or virtual enterprise and not the closed supply chain system where partners have already reached the agreement on the vocabulary to be used. In such a setting supply chain partnerships are created dynamically and last only for a short period. The ontology was developed with no specific industry focus and consists of the following top-level classes: Supply_Chain, SC_Structure, Party, Role, Purpose, Activity, Resource, Transfer_Object, Performance and Performance_Metric. These were further specialized although no information about the lower level classes is provided. It was originally conceptualized in Protégé and subsequently coded in OWL to enable web-based supply chain integration. The ontology model by Ye et al. provided the semantic backbone for an integration framework. This framework was then used in an imaginary supply chain scenario to solve the problem of supply chain information integration.

4. Comparison framework

This section presents the design of the comparison framework used to analyse the six supply chain ontology models selected. This framework consists of seven evaluation criteria which are presented in Table 1 along with their respective dimensions. The criteria were developed from analysis of literature in general ontology development and SCM.

4.1. Conceptualization or scientific paradigm

This criterion aims to identify the underlying scientific paradigm of a supply chain ontology model. There is significant similarity between conceptualization as used and introduced in ontology research (mainly AI and information systems) and the notion of scientific paradigm as introduced in the history and philosophy of science literature. Smith [35] claims that one of the reasons why information system ontologies have failed is because these were treated as equal and it was not recognized that conceptualizations to which different information system ontologies are committed to are not only of unequal quality but also mutually inconsistent.

In his widely cited paper, Gruber [66] defines ontology as "an explicit specification of conceptualization" (p. 199). This definition has been widely adopted in such a short period of time that ontology is sometimes mistakenly taken as a synonym for conceptualization. Guarino [67] claims that ontologies and conceptualizations are different and should be kept clearly distinct. In its broadest sense conceptualization always reflects a world view and the notion is often used as a synonym for scientific paradigm [68] which is characterized [69] by the two dimensions: ontological and epistemological. The notion of conceptualization was introduced by Genesereth and Nilsson [70] which is often used to accompany and further elaborate the higher level definition of ontology. Conceptualization is there defined as "the objects, concepts and other entities that are assumed to exist in some area of interest and their inter-relationships." According to Guarino [67]

Table 1
Evaluation framework.

Criteria	Dimensions of the criteria
1. Conceptualization/scientific paradigm	Objectivist and subjectivist paradigm
2. Level of granularity	Strategic, tactical and operational
3. Methodological approach	Inspiration, induction, deduction, synthesis, collaboration and hybrid; evaluation
4. Scope	Internal supply chain, dyadic relationship, external supply chain and inter-business network
5. Industry sector	Automotive, aerospace, electronics or other
6. Purpose/aim	Purpose/aim of the model
7. Application	Application of the model

the main problem with this definition is its extensional interpretation of conceptualization where the latter as he further claims should be understood as an intensional rather than extensional artefact. The terms extensional and intensional are terms used in the set theory. Mizoguchi [71] defines the difference between extensional and intensional sets in a way that the former is defined as consisted by enumerating all the elements while the latter only by specifying necessary and sufficient conditions for its elements. Definition of an intensional set introduced here resembles the idea of concept from the concept theory and that of a class from the object-oriented programming. According to concept theory a concept is defined intentionally as a collection of properties while instances possessing those properties constitute its extensions [72]. The idea of a class and categorization is central to ontology development. Thus, Sowa [73] claims that "the first step in designing a database, a knowledge-base, or an object-oriented system is to select an appropriate collection of ontological categories." (p. 670). Given that ontology always commits to a conceptualization and since the latter should be defined as an intentional set by specifying necessary and sufficient conditions for its elements, then it would not be hard to imagine that different people would specify different conditions which would result in different categorizations. The reason for this ought to be found in the way how people organize and structure their knowledge, that is epistemology, and not how the real world is structured (ontology). According to Parsons and Wand [74], classification structure is not inherent to the real world but constructed by us, that is, they claim that "things exist, but classes are constructed." (p. 238). Further to this, Parsons and Wand [75] claim that the reason why people use classification should be searched for in cognitive psychology and linguistics and not in ontology.

As elaborated, there is a strong relationship between ontology, conceptualization and scientific paradigm. The inconsistency in ontologies could be attributed to differences which exist among different sometimes even opposing scientific paradigms.

Scientific paradigm is characterized by two dimensions: ontological and epistemological; where both dimensions are further characterized by two extreme poles. Ontological by: realism and nominalism; and epistemological by: positivism and interpretivism [69]. The realism postulates that reality exists independently of the observer while nominalism postulates that reality is subjective construction. Epistemology is concerned with the knowledge about reality and what can be considered as valid knowledge of that reality. The positivistic epistemological stand centres on the identification of causal relationships by which observable phenomenon is explained. The interpretivist approach holds that understanding of some domain depends on the observer's pre-understanding of that domain. Although these poles define different paradigmatic stands, Klein and Hirschheim [69] claim that only two are significant for data modelling: objectivist and subjectivist paradigm. The former is defined by realist-positivist position and the latter with nominalist-interpretivist position. Although proposed for data modelling purposes, this is also useful for comparing supply chain ontology models. Therefore the conceptualization or scientific paradigm criterion is defined by these two paradigmatic stands.

4.2. Granularity

Every domain, including supply chain, can be enquired from different levels of conceptualization or granularity. The granularity criterion has been inspired by Guarino [67] who proposed a solution to a so-called interaction problem that has originated in the AI community. According to Schreiber et al. [76], the interaction problem states that "control knowledge and domain knowledge are highly dependent—one cannot define the domain knowledge without knowing what the task is going to be, and vice versa" (p. 33). Control knowledge is also called task solving knowledge where the domain knowledge represents pieces of domain knowledge relevant for employing the task solving knowledge. The interaction problem has generated a lot of academic debates [67,77]. In his papers Guarino [39,67] strongly defends the thesis of independence between domain and problem-solving knowledge and presents quite a few arguments. He does not recognize the interaction problem as a problem of dependence between domain and task knowledge, what he sees as dependent on a particular task is granularity of domain knowledge. In AI domain it is common to use different levels of conceptualization to reflect different granularities of a domain. Falkenhainer and Forbus [78] and Abu-Hanna and Jansweijer [79] have both used representation of different granularities of domain knowledge in order to solve engineering problems that demand different levels of abstraction. In Hobbs [80], granularity has also been included as the first of the core theories of ontology, where granularity is defined by "indistinguishability" relation or equivalently a set covering (p. 821). The granularity as introduced in Hobbs resembles to mereology or the theory of part-whole (see for example Refs. [39,81–83]), especially if we consider what Smith [35] says about mereology: "mereology allows ontologists to begin their investigations with complex wholes as it were on the middle level of reality, and to work upwards and downwards from these, as corresponding coarser and finer grained theories become available." Seen from this perspective, the interaction problem indeed reduces to the level of conceptualization required to solve a particular task.

Rudberg et al. [84] claim that SCM can be divided into two parts: supply chain planning and supply chain execution. They further state that the only difference between these two is in their respective time horizons, the former being more strategic and tactical, and the latter being more tactical and operational. A common view in the SCM community is that the granularity of supply chain decisions transcends three levels—strategic, tactical and operational [85]. Therefore these dimensions have been adopted to characterize the level of granularity criterion.

4.3. Methodological approach

This criterion aims to detect the underlying methodological approach adopted for the supply chain ontology development. Gruber [86] proposes a set of principles that should be used in the design of ontologies for knowledge sharing and Uschold and Gruninger [87] present an elaborate introduction into principles, methods and applications of ontologies. Kishore et al. [36] propose guidelines for ontology construction. They are based on two premises: (1) no ontology is ever complete; and (2) no methodology is perfect. They further argue that the best one can do is to follow a set of guidelines. Based on a so-called three layer guidelines, Mizoguchi [88] also introduces ontology development methodology and Noy and McGuinness [89] present a simple ontology development methodology aimed to be used by a novice and inexperienced ontology developer. Because of the multifaceted nature of ontology that requires capturing different views on a domain, collaborative ontology development has recently gained a wider interest. Holsapple and Joshi [90,91] present the collaborative approach to ontology development in the knowledge management discipline that uses the Delphi method. Apart from these approaches which could be characterized as less formal or detailed, the literature also recognizes other approaches [92–96] that are more formal and more detailed. These ontology development methodologies differ in various ways, such as: level of formality proposed, the approach chosen, domain for which the ontology is being developed, the portion of the ontology life-cycle addressed by the methodology, the maturity of methodology, and inheritance of a methodology. Nevertheless, quite a few authors [95,97–99] claim that ontology development is still an art rather than science which is not mature enough to ensure a valid ontology construction process.

This paper builds on the five general approaches to ontology design of Holsapple and Joshi [91]: (1) inspiration; (2) induction; (3) deduction; (4) synthesis; and (5) collaboration. The inspirational approach aims to capture an individual viewpoint about the domain while the induction approach involves the use of exploratory strategies. Deduction builds on the theoretical principles pertinent to the domain of interest while the synthesis approach aims to identify and integrate existing ontologies to characterize some aspects of a domain not covered by the ontology being developed. The collaborative approach recognizes the existence of multiple views on domain and tries to capture and/or reconcile them. The sixth approach further proposed here represents a hybrid or combinatorial approach consisting of at least two or more approaches. In addition to these six approaches, the supply chain ontology model is also analysed for the evaluation done.

4.4. Scope or organizational extent

This criterion aims to capture the organizational extent represented in a supply chain ontology model. In the seminal work on SCM, Christopher [100] defines SCM as: "the management of upstream and downstream relationships with suppliers and customers to deliver superior customer value at less cost to the supply chain as a whole." (p. 5). This definition clearly delineates inter-organizational nature of supply chains. Very similar is found in another seminal work by Lambert et al. [101] where they provide definition of SCM as "the integration of key business processes from end user through original suppliers that provide products, services and information that add value for customers and other stakeholders" (p. 1). Based on the extensive review of various definitions of SCM which was further extended by employing the systems approach, Harland [41] identifies four systems levels of SCM: (1) internal supply chain; (2) dyadic relationship; (3) external supply chain; and (4) inter-business network. While the first two levels aim to integrate and manage flow of materials and information within a company and two party relationships respectively; the latter two focus on chain and network of businesses. It is argued here that these four levels capture the different organizational relationships in a supply chain and provide an excellent characterization for the scope criterion.

4.5. Industry sector, purpose and application criteria

The last three criteria of the comparison framework are self-explanatory. The industry sector criterion describes the industry (e.g. automotive, aerospace, electronics, etc.) being addressed by the ontology model under consideration. Although certain commonalities across industry sectors exist, each sector also comes with some intrinsic specificity. The other two criteria communicate the purpose/aim of the supply chain ontology and any of its applications respectively.

5. Analysis of supply chain ontology models

This section reports on the analysis using the comparison framework. The analysis presented here provides insights about the gaps in existing supply chain ontology research.

5.1. Enterprise ontology—analysis

The way that EO selects and defines its constructs suggests the use of the objectivist paradigm. It was said before that EO does not address any aspect of a supply chain whatsoever hence no granularity level is attributed. The methodology proposed by Uschold and King [93] has been used in its development. This methodology consists of two parts: informal and formal ontology development. The informal part is concerned with the identification and development of relevant concepts and their natural language definitions; while the formal part converts these into Ontolingua definitions. Ontolingua is developed to be used as interchange format [66] and is based on first-order logic and enables object-oriented style of representation. Identification of the relevant concepts in the informal part is based on brainstorming thus it could be argued that the inspirational approach was used. The EO (both informal and formal) consists of five sections, where the first section (Meta-Ontology and Time) defines generic terms of Entity, Relationship and Role which are founding constructs for the development of terms which make the other four sections. Therefore, it could be stated that the synthesis approach was used. The ontology was assessed based on the actual uses against its original purposes. It was used in four different applications with varying aims and results. The majority of applications (three out of four) aimed to enhance human communication in an organization.

In applying the 'philosophy of science' lens in this analysis, EO equates ontology with knowledge of an enterprise ([53] p. 75 for example) which points to some ontological 'deficiencies' that might have arisen because of too much emphasis on enterprise knowledge rather than enterprise ontology. An example is the definition of the Meta-Ontology concept of Role. This concept is one of the founding concepts and is being used extensively in EO. It has been represented in Ontolingua as the Role-Class and it represents the way an Entity participates in a Relationship which in turn is modelled as an Entity. The Entity concept was defined as "a fundamental thing in the domain being modelled." (p. 43). The 'philosophy' question is: is a Relationship an Entity and does a Relationship exist in the enterprise domain or in any other domain in general? It is argued here that Relationship is a property of an Entity and as such it cannot exist independently of it. The rationale for this is based on findings of an extensive ontological analysis of a relationship construct reported in Wand et al. [102].

5.2. TOVE ontologies—analysis

Only the resource and organization ontologies of TOVE are relevant in the supply chain domain and analysed here. Similar to the EO, the TOVE ontologies also adopts the objectivist paradigm. This is best observed in a premise of common goals and no self-interests among agents. Also, both ontologies describe general and high level concepts that are structured into taxonomies. We conclude that a strategic level of granularity is adopted with no specific industry sector addressed. Since the activity-state-time ontology acts as a top-level ontology it could also be argued that a synthesis approach is taken while developing both ontologies.

Apart from adopting the activity-state-time ontology, a methodology proposed by Grüninger and Fox [92] was followed. This methodology dictates that ontology requirements would be defined in a form of competency questions which are posed by the ontology developer. Since no guidelines on defining the questions are provided it could be argued that their definition is a function of a previous experience and knowledge of a developer and therefore inspirational approach was followed. A strong AI legacy manifests throughout the TOVE ontologies, as the purpose of ontologies was to deduce answers to queries. This resulted in a strong emphasis on knowledge, rather than reality. There are examples in the organizational object taxonomy where some of the objects introduced have no ontological basis (e.g. the object Skill which cannot exist independently of its holder). One of the biggest advantages of the organization ontology is the formal introduction of the concept of Empowerment which models the right of an agent to perform some status changing actions. This concept – very similar to the concept of Authority in the EO – is used to link the structure and behaviour of the organization. The application of the TOVE ontologies is the TOVE Testbed (http://www.eil.utoronto.ca/iscm/index.html), which was developed as an environment to analyse enterprise ontologies.

5.3. Model by Soares et al.—analysis

Since this ontology builds on the EO (more specifically the Meta-Ontology), it was deduced that the objectivist paradigm was adopted. When compared to the TOVE ontologies, the ontology by Soares et al. is at a similar level of granularity. This lead to the conclusion that the ontology reviewed here is characterized on a strategic level.

A threefold hybrid methodological approach was adopted. The generic techno-organizational requirements of the semiconductor virtual enterprise have firstly been identified by reviewing literature related to virtual enterprise, using the deductive approach. The overall methodology used was one proposed by Uschold and King [93] and used in the development of the EO. Since this methodology is characterized by the use of brainstorming technique to elicit ontology requirements it follows that inspirational approach was also used. The foundation of this ontology is the Meta-Ontology of EO; therefore the synthesis approach was followed as well. There was no formal evaluation presented but since the methodology for the development of EO was used, it could be the case that similar evaluation approach was followed also. Though the authors mention that their approach is being tested no application of the ontology has been reported in the paper.

5.4. IDEON ontology—analysis

The IDEON ontology uses the objectivist paradigm since the idea of enterprises collaborating to achieve a common goal is a real world phenomenon. This ontology was developed by employing four perspectives to capture the different concepts and relationships which describe an enterprise. The views and their corresponding concepts aim to address the strategic level of supply chain granularity. The IDEON ontology addresses virtual enterprise and corresponds to the inter-business network scope of supply chain. The ontology was developed with no specific industry sector focus although the authors claim that the IDEON ontology is readily extensible to accommodate various application domains from health care to military command and control. Only two of the numerous enterprise applications the authors claim that the IDEON ontology was used to support have been briefly mentioned. The first is crisis action planning and execution and second is integrated product-process development. In both cases the ontology developed was used to provide the underlying conceptual framework.

No information was provided on the methodological approach used or the evaluation of the ontology. It is assumed that the inspirational approach was followed that the ontology is largely based on "knowledge and experience" rather than rigorous ontological analysis. This may be the reason for the many ontological deficiencies present in the model. For example the Enterprise Context View includes concepts of Assessment and Observation while the Resource/Product View includes the concept of Role. It is argued that these concepts do not exist independently in reality; rather they should be modelled as properties.

5.5. Manufacturing system engineering ontology—analysis

Only the seven top-level classes of the MSE ontology have been detailed, which represent rather high-level and generic constructs, it was concluded that the objectivist paradigm and strategic level of granularity have been adopted. Apart from referring to the manufacturing system information models [103–106] as an input for the MSE ontology no further information is provided about the ontology development. It is argued that the synthesis approach was used. Lin and Harding [64] offer an application of the MSE ontology that serves as a mediating ontology to enable information interoperability for inter-enterprise collaboration. For this purpose they have introduced a scenario (assume imaginary) of solving the information interoperability conflicts between different MSE software systems in a virtual manufacturing setting in the electronics industry sector. The MSE ontology developed served as an Interlingua by enabling mappings between individual ontologies. The Resource Description Framework (RDF), RDF Schema and Web Ontology Language (OWL) were used to facilitate the mappings.

From the 'philosophy of science' view, there are two major issues with the MSE ontology. The first relates to the strong emphasis being put on solving the terminological issues by using the MSE ontology as a mediator to enable mappings between different software systems. Although ontology can greatly reduce problems that are created due to inconsistent and varying vocabularies used, this is not its primary and ultimate goal. The second is the methodological approach of the MSE ontology development. The MSE ontology is heavily based on using different manufacturing system information models. Researches presented in [72,102,107] point to the potential faulty requirements and lack of rigorous analysis inherent in the information model development process. Therefore, it would not be surprising if the MSE ontology model inherits some ontological deficiencies introduced from the source models.

5.6. Model by Ye et al.—analysis

Based on the view that supply chain partners share the common purpose and objective with no self-centric and antagonistic behaviours, the objectivist paradigm was adopted. Comparing the top-level classes in the model with other supply chain ontology models that have the same scope (model by Soares et al., IDEON ontology, MSE ontology), the level of granularity corresponds to the strategic level.

The methodology employed is a hybrid of: inspiration, synthesis and deduction. The EO was used as the major backbone for this ontology model. It is fairly reasonable to conclude that the same methodological approaches are followed, thus inspiration and synthesis. The deductive approach was identified based on the use of the Supply Chain Operations Reference model [108]. This model was used as a source to capture the supply chain performance elements of the ontology model. The ontology provided a semantic backbone for the integration framework. This framework was then used on an imaginary supply chain scenario to solve the problem of supply chain information integration.

From the 'philosophy of science' point of view, this supply chain ontology has two major issues. The first relates to the perception that ontology development is only to solve terminology problem. The second issue concerns the model's ontological deficiencies. These deficiencies not only include those intrinsic to the EO which provided a backbone for the model but some newly created as well. An example for this is a class Service which is a subclass of a Material_Object. This implies that every Service object is a Material_Object which does have any ontological basis.

The overall analysis results for the six supply chain ontology models are presented in Table 2.

Table 2
Analysis results.

Supply chain ontology model	Criteria						
	Conceptualization/ scientific paradigm	Level of granularity	Methodological approach	Scope	Industry sector	Purpose/aim	Application
Enterprise ontology	Objectivist paradigm	Not applicable	Hybrid: inspiration and synthesis; evaluation: there is no formal evaluation although the ontology was assessed based on its actual uses against the original purposes.	Not applicable	No reference to industry sector	Three main intended uses of the ontology are: (1) enhance communication between humans; (2) providing a basis for specifying the end-user applications; and (3) support interoperability.	Four applications have been reported: (1) the use of the ontology in the Enterprise Tool Set to facilitate integration of software tools; (2) bid analysis process; (3) market analysis; and (4) continuous process improvement. The last three applications aimed to enhance human communication in an organization.
TOVE ontologies	Objectivist paradigm	Strategic	Hybrid: inspiration and synthesis; evaluation—there is no formal evaluation yet the ontology developed should comply to the competency questions posed at the beginning.	Internal supply chain	No reference to industry sector	To support the development of Enterprise Model which will have the ability to deduce answers to queries in industrial environments.	TOVE test bed to analyse enterprise ontologies.
Model by Soares et al.	Objectivist paradigm (since EO is the founding ontology)	Strategic	Hybrid: deduction (generic techno-organizational requirements), inspiration (since methodology by Uschold and King [93] was followed) and synthesis (since EO was thoroughly used); evaluation—probably similar as with the evaluation of EO.	Inter-business network	Electronics (semiconductor)	To improve communication required for the identification, specification and development of production planning and control system to support a virtual enterprise.	The authors mention that approach is being successfully tested and evaluated although no specific application is reported.
IDEON ontology	Objectivist paradigm	Strategic	Inspiration (assumed); evaluation—there is no evidence on any formal or informal evaluation.	Inter-business network	No reference to industry sector—claiming to be general enough	To provide foundation for designing, reinventing, managing and controlling collaborative and distributed enterprises.	Two applications have been reported: (1) crisis action planning and execution; and (2) integrated product-process development. These applications were described in a rather limited manner.
Manufacturing system engineering ontology	Objectivist paradigm	Strategic	Synthesis—built on the experiences and knowledge of published manufacturing system information models. Evaluation—no formal evaluation is introduced.	Inter-business network	Electronics	By providing a common framework of manufacturing-related terms it is developed to enable semantic interoperability of manufacturing system engineering applications as well as knowledge reuse within the global extended manufacturing setting.	The proposed ontology was used as a mediating ontology to enable information interoperability for inter-enterprise collaboration.
Model by Ye et al.	Objectivist paradigm	Strategic	Hybrid: inspiration and synthesis since the same methodology for the development of EO was used; also deduction (limited extent) since SCOR model was used for supply chain performance; evaluation—probably similar as with the evaluation of EO.	Inter-business network	No reference to industry sector	To serve as an Interlingua by enabling the semantic integration between heterogeneous systems in a supply chain.	A supply chain application integration framework based on the developed ontology is proposed. This framework was then used on an imaginary supply chain scenario to solve the problem of information integration. Also, the ontology developed was used to propose implementation architecture for supply chain integration.

6. Gaps in supply chain ontology models

Building on the analysis results of the previous section, this section synthesises and summarises the major gaps in existing supply chain ontology models. The synthesis consists of two parts. The first reflects on the analysis results from Table 2 while the second introduces some other gaps deduced from the comparison analysis.

6.1. Gaps based on analysis results

Three gaps were synthesised directly from the comparison table.

6.1.1. Gap 1: the granularity is only at the strategic level

The first gap concerns the level of granularity addressed by supply chain ontology models. There is no work into the tactical and operational levels, which are the levels to support planning and transaction supply chain operations.

6.1.2. Gap 2: the methodological approaches adopted are too remote from real supply chain

The most used approaches are inspiration and synthesis. It seems that supply chain ontology development has been inspirational endeavour that depends heavily on the robustness and comprehensiveness of top-level concepts adopted from other ontologies. The supply chain ontology researchers do not build enough from the vast theoretical base pertinent to SCM. It is also interesting to point out that the inductive and collaborative approaches are completely absent. In respect to the former it is deemed important to stress here that many researchers, especially in the field of operations management [109–112] and to it closely related fields of logistics and SCM [113], have stressed that more theory building through empirical or field based research is required. This gap is further justified by the comparison results for industry sector criterion. Apart from the model by Soares et al. and the MSE ontology no specific industry sector is being addressed. According to Table 2, formal ontology evaluation is not practiced and the collaborative approach could be used in a manner where the developed ontology is validated by its users.

6.1.3. Gap 3: a very limited view on the scope of supply chain

Apart from the EO and TOVE ontologies all other supply chain ontology models have inter-business network as its scope. There is no work to capture the ontology of dyadic relationships or external supply chains.

6.2. Other gaps not captured by the evaluation framework

Beyond the criteria in the comparison framework, additional gaps have also been identified during the analysis. Six gaps are further identified and presented next.

6.2.1. Gap 4: an explicit account of material traceability and service is missing

Supply chain development has highlighted the capability to track and trace materials as an important requirement and a very active research topic [114–117]. None of the models addresses this issue. Service has also grown as an important supply chain concept. Although all models have in a very limited degree acknowledged the concept of service, the material oriented view still dominates.

6.2.2. Gap 5: a static view on supply chain ontology prevails

Only the EO and TOVE ontologies have formally represented and acknowledged the importance of time. These models could therefore be characterized as dynamic. Other models have adopted a rather static view on a supply chain.

6.2.3. Gap 6: all of the work related to supply chain ontology is centred on the organization and structure of human knowledge of that reality rather than with the reality itself

As explained in Bateman [38], the majority of work on ontology in AI deals "with the organization and structure of human knowledge of reality rather than with the reality itself." (p. 931). The review of supply chain ontology models provides evidence where ontology of a domain is being equated with the knowledge of that domain. The majority of ontological deficiencies inherently present in these models could also be attributed to this. Hence, more rigorous and theoretically sound analysis is required to develop more realistic and robust supply chain systems.

6.2.4. Gap 7: a restricted view on a supply chain

By reviewing the supply chain ontology models one gets an impression that problems of supply chain are reduced to identifying the requirements of manufacturing activities. No formal account of other material and information flow supported activities (e.g. replenishment, transport, reverse logistics, etc.) is evident. Broader and more holistic approach is required in order to effectively develop and represent ontology of a supply chain.

6.2.5. Gap 8: taxonomic or class structure prevails

All models reviewed here have taxonomic or class–subclass structure. Although some classes overlap (e.g. Activity, Resource, Material, Strategy, Enterprise), big differences in class structures among the supply chain ontology models still exist. The perception of ontology being some sort of taxonomy prevails. Ontology is not the quest of finding class structure since the latter is in the realm of epistemology. Classification structure is not inherent to the real world but constructed by human, therefore the optimal class structure does not exist. The supply chain ontology models reviewed here urge the effort to identify a deeper order and structure of reality. Unfortunately, this is far more complex yet far more rewarding than developing a set of classes.

6.2.6. Gap 9: a perception that ontology reduces to mere terminological problems

The majority of supply chain ontology models aim to improve communication, either among humans (EO or model by Soares et al.) or between systems (MSE ontology or model by Ye et al.). The perception that ontology can solve interoperability problem by mapping terms between different systems is very evident. This view is largely founded on an assumption that the underlying conceptualizations that these systems comply to are equal and the only differences are those related to terms which are used to refer to different concepts. If this would really be the case then the solution to interoperability would be somewhat tedious but relatively simple. Unfortunately this is not the case since the underlying conceptualizations of those systems can be represented with conflicting paradigms with models which are not ontologically sound in the first place.

7. Conclusions

Supply chain ontology has lately been proposed as an important medium for solving information systems interoperability problems. In order to inform future supply chain ontology research, this paper set out to review and analyse existing supply chain ontology models. An extensive literature review was conducted which identified six supply chain ontology models together with seven criteria that form a comparison framework. Upon deploying the framework, nine gaps in existing supply chain ontology models have been identified which should provide insights into potential future research. The general conclusion is that we are still far from leveraging ontologies for solving information systems interoperability issues. Our analysis has shown that too much emphasis is being placed on the organization and structure of human knowledge of supply chains rather than with understanding the reality of supply chains.

Viewed from the ‘philosophy of science’ perspective, all the models reviewed have ontological deficiencies. More rigorous and theoretically sound analysis is required if more realistic and robust supply chain systems are to be developed. We urge supply chain ontology researchers to consider philosophical ontology especially the new developments such as: formal ontology, mereology, and topology. More effort should invested be in achieving a tighter relationship between the reality and our representations of that reality. Following this logic one might rightly doubt if supply chains as we “know” about exist. We argue that supply chain as an ontological concept or “thing” does not exist and is mistakenly taken as a unit of analysis. What really exist are flows of materials, information and services among supply chain companies. Therefore, these flows should be the starting point of analysis in the efforts to build supply chain ontology model.

This paper is the first rigorous and systematic attempt to identify and synthesise the research in the domain of supply chain ontology from a ‘philosophy of science’ perspective. A broad base of general ontology literature has been used to create a comparison framework to extract the most from ontology models and ensure the relevance of analysis results. Although some of the comparison criteria (scope and industry sector) are supply chain specific, we argue that other criteria are generic enough and can be used for the analysis of ontology models of any domain.

Acknowledgements

The authors are grateful to the UK’s Engineering and Physical Sciences Research Council and the industrial sponsors for providing support to the research through the grant GR/R68139/01 funding the Cranfield University Innovative Manufacturing Research Centre. The contribution from industrial collaborators and fellow team members Professor Alan Harrison, Mr Simon Templar and Mr Marko Bastl is acknowledged.

References

[1] K. Ramadas, R.E. Spekman, Chain or shackles: understanding what drives supply chain performance, Interfaces 30 (4) (2000) 3–21.
[2] M.T. Frohlich, R. Westbrook, Arcs of integration: an international study of supply chain strategies, Journal of Operations Management 19 (2) (2001) 185–200.
[3] E.D. Rosenzweig, A.V. Roth, J.W. Dean, The influence of an integration strategy on competitive capabilities and business performance: an exploratory study of consumer products manufacturers, Journal of Operations Management 21 (4) (2003) 437–456.
[4] R. Cagliano, F. Caniato, G. Spina, Lean, agile and traditional supply: how do they impact manufacturing performance? Journal of Purchasing & Supply Management 10 (4–5) (2004) 151–164.
[5] D.J. Bowersox, D.J. Closs, T.P. Stank, Ten mega-trends that will revolutionize supply chain logistics, Journal of Business Logistics 21 (2000) 1–16.
[6] K. Kumar, Technology for supporting Supply Chain Management, Communications of the ACM 44 (2001) 58–61.
[7] A.Z. Zeng, B.K. Pathak, Achieving information integration in supply chain management through B2B e-hubs: concepts and analyses, Industrial Management & Data Systems 103 (2003) 657–665.
[8] P. Buxmann, A. von Ahsen, L.M. Diaz, K. Wolf, Usage and evaluation of Supply Chain Management Software—results of an empirical study in the European automotive industry, Information Systems Journal 14 (2004) 295–309.
[9] T.H. Davenport, J.D. Brooks, Enterprise systems and the supply chain, Journal of Enterprise Information Management 17 (2004) 8–19.
[10] A. Gunasekaran, E.W.T. Ngai, Information systems in supply chain integration and management, European Journal of Operational Research 159 (2004) 269–295.
[11] K. Siau, Y. Tian, Supply chain integration: architecture and enabling technologies, The Journal of Computer Information Systems 44 (2004) 67–72.
[12] T.C. Loh, S.C.L. Koh, M. Simpson, An investigation of the value of becoming an extended enterprise, International Journal of Integrated Manufacturing 19 (2006) 49–58.
[13] R. Patnayakuni, A. Rai, N. Seth, Relational antecedents of information flow integration for supply chain coordination, Journal of Management Information Systems 23 (2006) 13–49.
[14] M.P. Papazoglou, P. Ribbers, A. Tsalgatidou, Integrated value chains and their implications from a business and technology standpoint, Decision Support Systems 29 (2000) 323–342.
[15] D. Chen, G. Doumeingts, European initiatives to develop interoperability of enterprise applications—basic concepts, framework and roadmap, Annual Reviews in Control 27 (2003) 153–162.
[16] S. Chopra, P. Meindl, What will drive the enterprise software shakeout? Supply Chain Management Review 7 (2003) 50–57.
[17] A. Huang, D.C. Yen, D.C. Chou, Y. Xu, Corporate applications integration: challenges, opportunities, and implementation strategies, Journal of Business and Management 9 (2003) 137–150.
[18] V. Botta-Genoulaz, P.-A. Millet, B. Grabot, A survey on the recent research literature on ERP systems, Computers in Industry 56 (2005) 510–522.
[19] M. Themistocleous, Z. Irani, R.M. O’Keefe, ERP and application integration: exploratory survey, Business Process Management Journal 7 (2001) 195–204.
[20] M. Themistocleous, Z. Irani, Benchmarking the benefits and barriers of application integration, Benchmarking: An International Journal 8 (2001) 317–331.
[21] T.H. Davenport, J.G. Harris, S. Cantrell, Enterprise systems and ongoing process change, Business Process Management Journal 10 (2004) 16–26.
[22] D. Sprott, Componentizing the enterprise application packages, Communications of the ACM 43 (2000) 63–69.
[23] W. Hasselbring, Information systems integration, Communications of the ACM 43 (2000) 33–38.
[24] K. Kumar, J. van Hillegersberg, ERP experiences and evolution, Communications of the ACM 43 (2000) 23–26.
[25] H.A. Akkermans, P. Bogerd, E. Yücesan, L.N. van Wassenhove, The impact of ERP on supply chain management: exploratory findings from a European Delphi study, European Journal of Operational Research 146 (2003) 284–301.
[26] R. Cagliano, F. Caniato, G. Spina, The linkage between supply chain integration and manufacturing improvement programmes, International Journal of Operations & Production Management 26 (2006) 282–299.
[27] T.H. Davenport, Putting the Enterprise into the Enterprise system, Harvard Business Review 76 (1998) 121–131.
[28] S. Zheng, D.C. Yen, J.M. Tarn, The new spectrum of the cross-enterprise solution: the integration of supply chain management and enterprise resource planning systems, The Journal of Computer Information Systems 41 (2000) 84–93.
[29] F.R. Jacobs, E. Bendoly, Enterprise resource planning: developments and directions for operations management research, European Journal of Operational Research 146 (2003) 233–240.
[30] B.J. Lee, K. Siau, S. Hong, Enterprise integration with ERP and EAI, Communications of the ACM 46 (2003) 184–205.
[31] P. Kelle, A. Akbulut, The role of ERP tools in supply chain information sharing, cooperation and cost optimization, International Journal of Production Economics 93–94 (2005) 41–52.
[32] C. Møller, ERP II: a conceptual framework for next-generation enterprise systems? Journal of Enterprise Information Management 18 (2005) 483–497.
[33] S. Pant, R. Sethi, M. Bhandari, Making sense of the e-supply chain landscape: an implementation framework, International Journal of Information Management 23 (2003) 201–221.
[34] N. Guarino, Formal ontology and information systems, in: Proceedings of FOIS’98, Trento, Italy, 6–8 June, IOS Press, Amsterdam, 1998, pp. 3–15.
[35] B. Smith, in: E.N. Zalta (Ed.), Ontology and Information Systems, The Stanford Encyclopaedia of Philosophy, Stanford, CA, 2003.
[36] R. Kishore, R. Sharman, R. Ramesh, Computational ontologies and information systems: I. Foundations, Communications of the Association for Information Systems 14 (2004) 158–183.
[37] P.A. Angeles, Dictionary of Philosophy, Harper Perennial, New York, 1981.
[38] J.A. Bateman, On the relationship between ontology construction and natural language: a socio-semiotic view, International Journal of Human-Computer Studies 43 (5–6) (1995) 929–944.
[39] N. Guarino, Formal ontology, conceptual analysis and knowledge representation, International Journal of Human-Computer Studies 43 (5–6) (1995) 625–640.
[40] D. Tranfield, D. Denyer, P. Smart, Towards a methodology for developing evidence-informed management knowledge by means of systematic review, British Journal of Management 14 (3) (2003) 207–222.
[41] C.M. Harland, Supply chain management: relationships, chains and networks, British Journal of Management 7 (s1) (1996) s63–s80.
[42] C. Chandra, A.K. Kamrani, Knowledge management for consumer-focused product design, Journal of Intelligent Manufacturing 14 (6) (2003) 557–580.
[43] H. Aziz, J. Gao, P. Maropoulos, W.M. Cheung, Open standard, open source and peer-to-peer tools and methods for collaborative product development, Computers in Industry 56 (3) (2005) 260–271.
[44] J. Cai, M. Weyrich, U. Berger, Ontological machining process data modelling for powertrain production in extended enterprise, Journal of Advanced Manufacturing Systems 4 (1) (2005) 69–82.
[45] W.M. Cheung, Ontological approach of organizational knowledge to support collaborative product development, Journal of Advanced Manufacturing Systems 5 (1) (2006) 3–25.

[46] O. Chira, C. Chira, T. Roche, D. Tormey, A. Brennan, An agent-based approach to knowledge management in distributed design, Journal of Intelligent Manufacturing 17 (6) (2006) 737–750.
[47] C.I.V. Kerr, R. Roy, P.J. Sackett, Requirements management: an enabler for concurrent engineering in the automotive industry, International Journal of Production Research 44 (9) (2006) 1703–1717.
[48] J.S. Arlbjørn, A. Halldorsson, Logistics knowledge creation: reflections on content, context and processes, International Journal of Physical Distribution & Logistics Management 32 (1) (2002) 22–40.
[49] J. Zhao, W.M. Cheung, R.I.M. Young, A consistent manufacturing data model to support virtual enterprise, International Journal of Agile Management Systems 1 (3) (1999) 150–158.
[50] A. McKay, A. de Pennington, Towards an integrated description of product, process and supply chain, International Journal of Technology Management 21 (3/4) (2001) 203–220.
[51] Y. Liu, R.I.M. Young, Utilizing information and knowledge models to support global manufacturing co-ordination decisions, International Journal of Computer Integrated Manufacturing 17 (6) (2004) 479–492.
[52] M. Rönkkö, M. Kärkkäinen, J. Holmström, Benefits of an item-centric enterprise-data model in logistics service: a case study, Computers in Industry 58 (8–90) (2007) 814–822.
[53] M. Uschold, M. King, S. Moralee, Y. Zorgios, The enterprise ontology, The Knowledge Engineering Review 13 (1) (1998) 31–89.
[54] M.S. Fox, M. Barbuceanu, M. Grüninger, An organization ontology for enterprise modelling: preliminary concepts for linking structure and behaviour, Computers in Industry 29 (1–2) (1996) 123–134.
[55] F.G. Fadel, M.S. Fox, M. Grüninger, A generic enterprise resource ontology, in: Proceedings of the Third IEEE Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises, West Virginia (WET ICE'94), April, (1994), pp. 117–128.
[56] K.D. Tham, M.S. Fox, M. Grüninger, A cost ontology for enterprise modelling, in: Proceedings of the Third IEEE Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises, West Virginia, April, (1994), pp. 111–117.
[57] M.S. Fox, M. Barbuceanu, M. Grüninger, J. Lin, An organization ontology for enterprise modelling, in: M. Prietula, K. Carley, L. Gasser (Eds.), Simulating Organizations: Computational Models of Institutions and Groups, AAAI/MIT Press, Menlo Park, 1998, pp. 131–152.
[58] J. Lin, M.S. Fox, T. Bilgic, A requirement ontology for engineering design, in: Proceedings of the 3rd International Conference on Concurrent Engineering, 1996, pp. 343–351.
[59] M.S. Fox, M. Grüninger, Enterprise modeling, AI Magazine Fall (1998) 109–121.
[60] H.M. Kim, M.S. Fox, M. Grüninger, An ontology for quality management-enabling quality problem identification and tracing, BT Technology Journal 17 (4) (1999) 131–140.
[61] A.L. Soares, A.L. Azevedo, J.P. De Sousa, Distributed planning and control systems for the virtual enterprise: organizational requirements and development life-cycle, Journal of Intelligent Manufacturing 11 (3) (2000) 253–270.
[62] A.M. Madni, W. Lin, C.C. Madni, IDEON™: an extensible ontology for designing, integrating and managing collaborative distributed enterprises, Systems Engineering 4 (1) (2001) 35–48.
[63] H.K. Lin, J.A. Harding, M. Shahbaz, Manufacturing system engineering ontology for semantic interoperability across extended project teams, International Journal of Production Research 42 (24) (2004) 5099–5118.
[64] H.K. Lin, J.A. Harding, A manufacturing system engineering ontology model on the semantic web for inter-enterprise collaboration, Computers in Industry 58 (5) (2007) 428–437.
[65] Y. Ye, D. Yang, Z. Jiang, L. Tong, An ontology-based architecture for implementing semantic integration of supply chain management, International Journal of Computer Integrated Manufacturing 21 (1) (2008) 1–18.
[66] T.R. Gruber, A translation approach to portable ontology specification, Knowledge Acquisition 5 (2) (1993) 199–220.
[67] N. Guarino, Understanding, building and using ontologies, International Journal of Human-Computer Studies 46 (2–3) (1997) 293–310.
[68] T.S. Kuhn, The Structure of Scientific Revolutions, 3rd edition, University of Chicago Press, Chicago, 1996.
[69] H.K. Klein, R.A. Hirschheim, A comparative framework of data modelling paradigms and approaches, The Computer Journal 30 (1) (1987) 8–15.
[70] M.R. Genesereth, N.J. Nilsson, Logical Foundation of Artificial Intelligence, Morgan Kauffman, Los Altos, CA, 1987.
[71] R. Mizoguchi, Tutorial on ontological engineering: advanced course of ontological engineering (Part 3), New Generation Computing 22 (2) (2004) 198–220.
[72] J. Parsons, An information model based on classification theory, Management Science 42 (10) (1996) 1437–1453.
[73] J.F. Sowa, Top-level ontological categories, International Journal of Human-Computer Studies 43 (5–6) (1995) 669–685.
[74] J. Parsons, Y. Wand, Emancipating instances from the tyranny of classes in information modeling, ACM Transactions on Database Systems 25 (2) (2000) 228–268.
[75] J. Parsons, Y. Wand, Choosing classes in conceptual modeling, Communications of the ACM 40 (6) (1997) 63–69.
[76] G. Schreiber, B. Wielinga, R.R. de Hoog, H. Akkermans, W. Van de Velde, CommonKADS: a comprehensive methodology for KBS development, IEEE Expert 9 (6) (1994) 28–37.
[77] G. van Heijst, A.T. Schreiber, B.J. Wielinga, Roles are not classes: a reply to Nicola Guarino, International Journal of Human-Computer Studies 46 (2–3) (1997) 311–318.
[78] B. Falkenhainer, K.D. Forbus, Compositional modeling: finding the right model for the job, Artificial Intelligence 51 (1–3) (1991) 95–143.
[79] A. Abu-Hanna, W. Jansweijer, Modelling domain knowledge using explicit conceptualization, IEEE Expert 9 (5) (1994) 53–64.
[80] J.R. Hobbs, Sketch of an ontology underlying the way we talk about the world, International Journal of Human-Computer Studies 43 (5–6) (1995) 819–830.
[81] M.E. Winston, R. Chaffin, D. Herrmann, A taxonomy of part-whole relations, Cognitive Science 11 (4) (1987) 417–444.
[82] B. Smith, Mereotopology: a theory of parts and boundaries, Data & Knowledge Engineering 20 (3) (1996) 287–303.
[83] A.C. Varzi, Parts, wholes, and part-whole relations: the prospects of mereotopology, Data & Knowledge Engineering 20 (3) (1996) 259–286.
[84] M. Rudberg, N. Klingenberg, K. Kronhamn, Collaborative supply chain planning using electronic marketplaces, Integrated Manufacturing Systems 13 (8) (2002) 596–610.
[85] K.L. Croxton, S.J. García-Dastague, D.M. Lambert, D.S. Rogers, The supply chain management processes, The International Journal of Logistics Management 12 (2) (2001) 13–36.
[86] T.R. Gruber, Towards principles for the design of ontologies used for knowledge sharing, International Journal of Human-Computer Studies 43 (5–6) (1995) 907–928.
[87] M. Uschold, M. Gruninger, Ontologies: principles, methods and applications, The Knowledge Engineering Review 11 (1996) 93–155.
[88] R. Mizoguchi, Tutorial on ontological engineering: ontology development, tools and languages (Part 2), New Generation Computing 22 (1) (2003) 61–96.
[89] N.F. Noy, D.L. McGuinness, Ontology Development 101: A Guide to Creating Your First Ontology, Stanford University, Stanford, CA, 2002, Stanford Medical Informatics Report SMI-2001-0880.
[90] C.W. Holsapple, K.D. Joshi, Organizational knowledge resources, Decision Support Systems 31 (1) (2001) 39–54.
[91] C.W. Holsapple, K.D. Joshi, A collaborative approach to ontology design, Communications of the ACM 45 (2) (2002) 42–47.
[92] M. Grüninger, M.S. Fox, Methodology for the design and evaluation of ontologies, in: Proceedings of the IJCAI'95, Workshop on Basic Ontological Issues in Knowledge Sharing, Montreal, Canada, 1995.
[93] M. Uschold, M. King, Towards methodology for building ontologies, in: Proceedings of the IJCAI-95, Workshop on Basic Ontological Issues in Knowledge Sharing, Montreal, Canada, 1995.
[94] B. Swartout, P. Ramesh, K. Knight, T. Russ, Toward distributed use of large-scale ontologies, in: Symposium on Ontological Engineering of AAAI, 1997, 138–148.
[95] M. Fernández-López, A. Gómez-Pérez, J.P. Sierra, A.P. Sierra, Building a chemical ontology using Methontology and the ontology design environment, IEEE Intelligent Systems 14 (1) (1999) 37–46.
[96] S. Staab, R. Studer, H.-P. Schnurr, Y. Sure, Knowledge processes and ontologies, IEEE Intelligent Systems 16 (1) (2001) 26–34.
[97] D. Jones, T. Bench-Capon, P. Visser, Methodologies for ontology development, in: Proceedings of IT&KNOWS Conference, XV IFIP World Computer Congress, Budapest, Hungary, (1998), pp. 62–75.
[98] M. Fernández-López, A. Gómez-Pérez, Overview and analysis of methodologies for building ontologies, The Knowledge Engineering Review 17 (2) (2002) 129–156.
[99] R. Mizoguchi, Tutorial on ontological engineering: introduction to ontological engineering (Part 1), New Generation Computing 21 (4) (2003) 362–383.
[100] M. Christopher, Logistics and Supply Chain Management—Creating Value-Adding Networks, 3rd edition, Financial Times, Prentice Hall, London, UK, 2005 .
[101] D.M. Lambert, M.C. Cooper, J.D. Pagh, Supply chain management: implementation issues and research opportunities, The International Journal of Logistics Management 9 (2) (1998) 1–19.
[102] Y. Wand, V.C. Storey, R. Weber, An ontological analysis of the relationship construct in conceptual modeling, ACM Transactions on Database Systems 24 (4) (1999) 494–528.
[103] J.A. Harding, A.R. Omar, K. Popplewell, Application of QFD within a concurrent engineering environment, International Journal of Agile Management Systems 1 (2) (1999) 88–98.
[104] K. Kosanke, F. Vernadat, M. Zelm, CIMOSA: enterprise engineering and integration, Computers in Industry 40 (2–3) (1999) 83–97.
[105] J. Zhao, W. Cheung, R.I. Young, R. Bell, An object oriented manufacturing data model for a global enterprise, in: Proceedings of the Third 15th International Conference on Computer-Aided Production Engineering (CAPE '99), Durham, UK, April, (1999), pp. 582–588.
[106] J.A. Harding, K. Popplewell, D. Cook, A manufacturing system engineering moderator: an aid for multi-discipline project teams, International Journal of Production Research 41 (9) (2003) 1973–1986.
[107] Y. Wand, R. Weber, Research commentary: information systems and conceptual modeling—a research agenda, Information Systems Research 13 (4) (2002) 363–376.
[108] http://www.supply-chain.org.
[109] B.B. Flynn, S. Sakakibara, R.G. Schroeder, K.A. Bates, E.J. Flynn, Empirical research methods in operations management, Journal of Operations Management 9 (2) (1990) 250–284.
[110] D.M. McCutcheon, J.R. Meredith, Conducting case study research in operations management, Journal of Operations Management 11 (3) (1993) 239–256.
[111] J.R. Meredith, Theory building through conceptual methods, International Journal of Operations & Production Management 13 (5) (1993) 3–11.

[112] C. Voss, N. Tsikriktsis, M. Frohlich, Case research in operations management, International Journal of Operations & Production Management 22 (2) (2002) 195–219.
[113] A. Sachan, S. Datta, Review of supply chain management and logistics research, International Journal of Physical Distribution & Logistics Management 35 (9) (2005) 664–705.
[114] M.H. Jansen-Vullers, C.A. van Dorp, A.J.M. Beulens, Managing traceability information in manufacture, International Journal of Information Management 23 (5) (2003) 395–413.
[115] T. Kelepouris, K. Pramatari, G. Doukidis, RFID-enabled traceability in the food supply chain, Industrial Management & Data Systems 107 (2) (2007) 183–200.
[116] A. Bechini, M.G.C.A. Cimino, F. Marcelloni, A. Tomasi, Patterns and technologies for enabling supply chain traceability through collaborative e-business, Information and Software Technology 50 (4) (2007) 342–359.
[117] J.G. Campos, R.M. Martin, J.S. Lopez, J.I. Armesto, A traceability model for spread manufacturing environments, WSEAS Transactions on Systems 6 (3) (2007) 520–527.

Tonci Grubic is a research fellow at Integrated Vehicle Health Management (IVHM) Centre at Cranfield University. IVHM is the use of hardware and software technologies that provide information on the condition or "health" of a product, both current and predicted, and its use to enhance operational decisions. Currently he is working on a research project which aims to map the high value applications of IVHM and create a simulation tool that companies can apply to evaluate the potential of IVHM to their products and business. Before this, he worked as a research officer at Manufacturing Department of Cranfield University on a logistics and supply chain management research project that aimed to develop a business process model of a dyadic relationship. Prior to joining Cranfield University he was working at University of Split, Croatia where he gained BSc and MSc in Mechanical Engineering. He was involved there in teaching and research activities. Recently he submitted his Ph.D. which proposes a comprehensive supply chain process modelling approach founded on ontology. His research interests include: logistics and supply chain management, operations management, information systems, ontology engineering and computer modelling. He has authored or co-authored several papers in scientific journals and conference proceedings.

Ip-Shing Fan is currently the Course Director of the MSc in Enterprise System Implementation in Cranfield University, UK. He has interest in the effective design, development, implementation and use of ICT in business and non-business organizations. His work included the use of business process modelling and analysis to help business to improve performance through smarter way of working. The improvement approach integrates the use of organization and technology introduction with sensitive people change management. He has deliver consultancy to global businesses to help in different stages of ERP, PLM and SCM implementation. Using a socio-technical approach, he developed tools to provide organization and human factor readiness assessment for enterprise systems; and assist in formulating change management plans to improve the readiness. He gained his Ph.D. in Computer Integrated Manufacturing in Cranfield Institute of Technology and completed his Bachelor degree in Industrial Engineering in the University of Hong Kong.