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Towards a meaningful manufacturing enterprise metamodel: a semantic driven framework

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Abstract: This paper presents a deep investigation and an interdisciplinary analysis of the collaborative networked enterprise engineering issues and modelling approaches related to the relevant aspects of the semantic web technology and knowledge strategies. The paper also suggests a novel framework based on ontology metamodeling, knowledge model discovery, and semantic web infrastructures, architectures, languages, and systems. The main aim of the research enclosed in this paper is to bridge the gaps between enterprise engineering, modelling, and especially networking by intensively applying semantic web technology based on ontology conceptual representations and knowledge discovery. The ontological modelling approaches together with knowledge strategies such as discovery (data mining) have become promising for future enterprise computing systems. The related reported research deals with the conceptual definition of a semantic-driven framework and a manufacturing enterprise metamodel (ME.M) using ontology, knowledge-driven object models, standards, and architectural approaches applied to collaborative networked enterprises. The conceptual semantic framework and related issues discussed in this paper may contribute towards new approaches of enterprise systems engineering and networking as well as applied standard and referenced ontological models.

Keywords: enterprise engineering, manufacturing system engineering (MSE) ontological model, ontology definition metamodel (ODM), extended enterprise common warehouse metamodel (EE.CWM), manufacturing enterprise metamodel (ME.M)

1 INTRODUCTION AND OBJECTIVES

Generally, the current approaches of enterprise engineering deal with the analysis, design, implementation, and operation of single enterprises, but they provide basic mechanisms such as mappings and support tools for networking. The role of modelling and especially of information and knowledge model representations as a highly generic abstract view of an enterprise is a key issue in enterprise engineering and networking. On the other hand, modelling an enterprise as a complex and dynamic system or even 'as a system of systems' is directed at achieving

better understanding and perhaps simulation of the enterprise's functionalities, requirements, and behaviour, thus providing greater flexibility in re-design and re-engineering of the whole enterprise or some of its components/subsystems. Although there are several enterprise modelling methods and support languages such as CIM-OSA, SADT, IDEF family tools, etc., they may not adequately support the requirements of a collaborative networked enterprise, which can be defined as an extended or virtual enterprise. However, virtual enterprise approaches have also generated models, architectures, and methodologies such as VERA and VERAM [1], but they are mainly based on Generalized enterprise reference architecture and methodology (GERAM) [2, 3]. The enterprise engineering efforts and supporting technologies are graphically summarized

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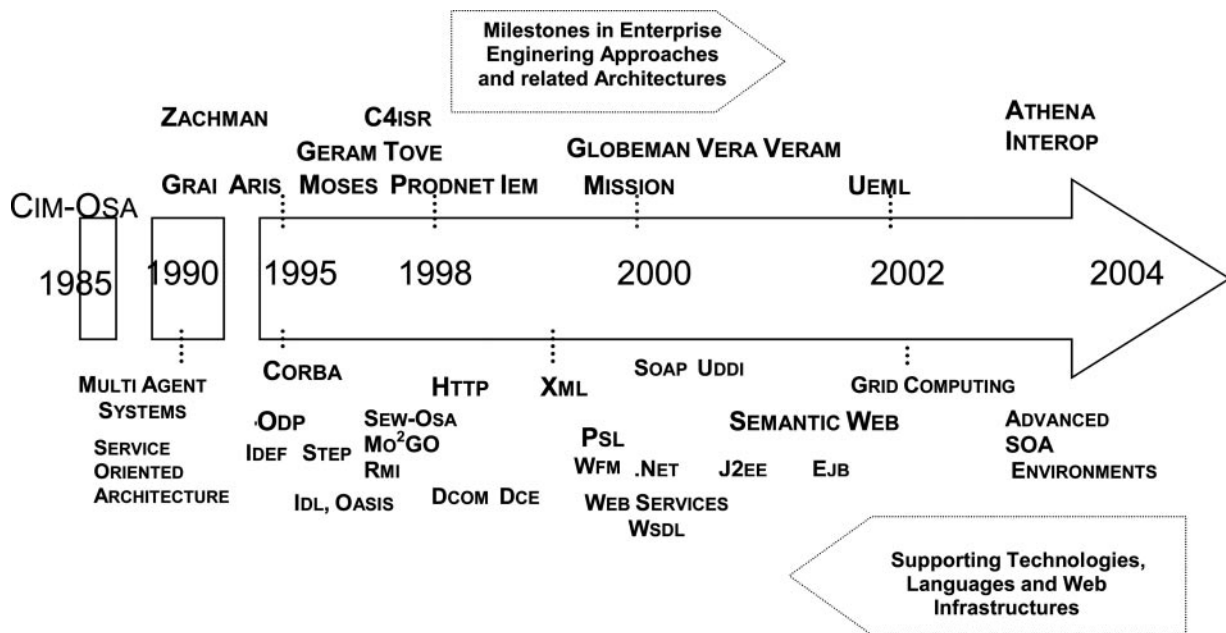


Fig. 1 Historical perspective of the enterprise engineering approaches

and shown in Fig. 1. The unified enterprise modelling language (UEML) proposed by Vernadat [4] has been directed at providing a uniform representation for enterprise modelling methodologies, systems, and tools, and a neutral format for exchanging enterprise models. Although Vernadat [4] has defined enterprise modelling as 'the art of externalizing enterprise knowledge, which adds value to the enterprise or needs to be shared', the implementation solutions of UEML, due to the level of technology development at that time, do not explicitly consider the emergence of the semantic web that uses ontology for modelling shared meanings, concepts, and theories.

The search for faster and optimal methods of design and manufacture has recently resulted in the need for greater information exchange or even knowledge sharing in supply chain partnerships or extended/virtual enterprise scenarios. In consequence, the challenges of 'getting the right information to the right person at the right time' and of effectively exploiting existing expertise and knowledge across multiple projects with different sets of collaborative partners is constantly increasing. There is huge potential for confusion or ambiguity in meaning and there are many examples of the costs associated with the type of information failure. For example, a failure to recognize and correct an error in the transfer of information between the Mars Climate Orbiter spacecraft team in Colorado and the mission navigation team in California led to the loss of the spacecraft [5]. The findings of NASA's Laboratory demonstrated that the error was caused

because the information supplied from the team in Colorado was in English units, but it was assumed to be metric by the team in California. Therefore, for several aspects of enhanced collaborative work including extended/virtual enterprise much greater links need to be established between the modelling approaches – facilitating the sharing of knowledge and semantic web technology – which can clarify the meaning and reduce ambiguity within information and knowledge using vocabularies, ontologies, taxonomies, and advanced dictionaries.

Lin [6] and Lin *et al.* [7] have demonstrated the benefits of semantic driven approaches that have a good potential in enterprise engineering, extended/global project teams work and e-collaboration. UEML represents a clear progress towards the unification of the enterprise modelling approaches and languages, especially by considering the enterprise domain semantics, but the most recent version (UEML 1.0) has not provided complete solutions using ontologies. This paper includes several issues related to both the UEML and the unified modelling language (UML), mainly defined by Rumbaugh *et al.* [8], and their application to the collaborative networked enterprise issues. Therefore it is necessary to emphasize that the name of UEML has been intentionally chosen to be similar to UML, but their purposes are quite different, as explained in reference [4]. Moreover, UML is mainly dedicated to computing and information systems analysis and development, and has been found to be too general for enterprise modelling. UEML is a dedicated language for enterprise modelling based on core

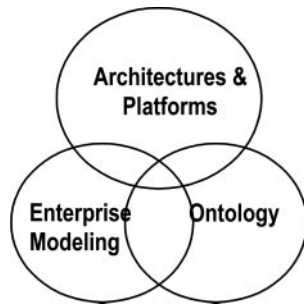


Fig. 2 INTEROP research areas

constructs, but is too restrictive for the research reported in this paper. Therefore, UML has been chosen for modelling purposes because of its generic representation of broad categories of information systems as well as its recent capabilities of ontology metamodeling, which will be detailed in the section 2, and is dedicated to research background.

More recently, ontologies, vocabularies, taxonomies, and associated business rules have become key components of a model-driven approach to enterprise modelling and computing that use semantic web technology for the development of related applications.

Within the FP6 network of excellence (NoE), interoperability research for networked enterprise applications and software (INTEROP), and the integrated project (IP), advanced technologies for interoperability of heterogeneous enterprise networks and their applications (ATHENA), there are also several efforts directed at providing ([9], <http://www.athena-ip.org/>, and [10], <http://www.interop-noe.org/>):

- (a) architectures, reference models, and enabling technologies aiming at the definition of the foundation and enterprise frameworks based on the latest architectural concepts and paradigms, such as service-oriented and semantic web;
- (b) enterprise modelling methods and tools for the achievement of interoperability requirements for systems, (meta)data, and communications, alongside the solutions that meet these requirements;
- (c) enterprise ontology for sharing/exchanging meaningful models and interoperable semantics in the enterprise as well as web-enabled infrastructures and semantic support systems;
- (d) advanced methods and infrastructures that enterprises can apply for the strategic management and organizational roles, skills, competencies, and knowledge assets for its operation and for collaboration with other enterprises.

The main research areas considered by the NoE INTEROP are presented in Fig. 2, while Fig. 3

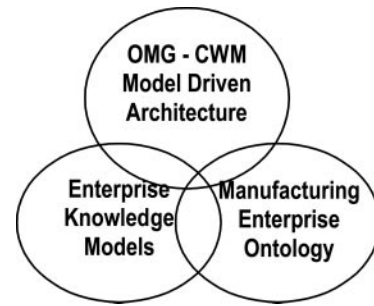


Fig. 3 Bridging generating gaps between enterprise, knowledge, and ontology

illustrates the main gaps that this paper intends to bridge based on previous theoretical approaches and practice related to the information and knowledge modelling and discovery as well as manufacturing system engineering ontology for semantic interoperability carried out at the Wolfson School of Mechanical and Manufacturing Engineering at Loughborough University. The model provided by Lin [6] has been designed to support a unified description of the terminology related to extended enterprise manufacturing system engineering functions while other models (e.g. PSL and STEP) cover particular aspects of manufacturing and design. Moreover, this paper defines a metamodel, which includes ontological representation, and a common knowledge enterprise model based on data mining. The definition of an enterprise metamodel based on ontology representations and knowledge discovery have not been addressed.

Therefore the research reported in this paper provides a framework for collaborative networked enterprise engineering based on semantic web languages such as RDF (resource description framework), DAML (DARPA agent markup language) + OIL (ontology interchange language and ontology interface layer), OWL (web ontology language) [11, 12], and an ontology definition metamodel (ODM) currently defined by the Object Management Group (OMG) [13]. Generally, the OMG produces and maintains software specifications for interoperability of enterprise and web applications. It provides well-established standards covering software production from design, through development, to deployment and maintenance, and supports a full-lifecycle approach to enterprise engineering, integration, networking, and information systems implementation.

The models and ontologies have an increasingly central role in enterprise systems engineering and related research, suggesting that modelling approaches have growing importance. On the one hand, the semantic web and/or knowledge engineering community is increasingly promoting ontologies as the key to better and non-ambiguous

systems engineering methods, while on the other hand the software engineering community is promoting model-driven development as the core solution. In some cases extended models and ontologies could be similar. This duality results in a need for comprehensive manufacturing enterprise models to be defined based on knowledge and ontologies. Existing (manufacturing) enterprise ontologies, thesauri as well as ontology/semantic discovery and related issues, are considered in order to build and maintain a flexible and dynamic semantic enterprise metamodel that will encompass the model evolution. The open key questions that have not been satisfactorily addressed by existing approaches relating to the application of ontologies and semantic webs for enterprise engineering are examined in this paper, and the limitations of the current approaches are analysed.

An interdisciplinary background related to the semantic web and collaborative networked enterprises is also needed and is provided in sections 2 and 3. Section 4 includes the description of a suggested manufacturing enterprise metamodel based on an existing top-level ontology, a common knowledge enterprise model, and the ODM (ontology definition metamodel) recently proposed by the OMG, which is introduced in section 2.1.

2 RESEARCH BACKGROUND

The ontology concept has its roots in philosophy and, from the perspective of knowledge sharing, Tom Gruber has defined it as 'an explicit specification of a conceptualization' [11]. Generally, it is possible to identify the following three generations of approaches related to ontology theory and practice.

First generation (circa 1985–1995). Defined and applied in the framework of developing knowledge-based systems and knowledge modelling, ontologies are mainly descriptive representations, even definitions related to domains, methods, and tasks. These approaches include CommonKADS, TOVE, and the earlier version of Protégé.

Second generation (circa 1995–present). In the context of semantic web technology, an ontology-based approach was adopted for dealing with heterogeneous data, and in particular for managing systems interoperability. Ontologies provide the conceptual underpinning that is required to define and communicate the semantics of metadata stored and/or processed data. Several efforts have been directed to formalize the web by powerful ontology and semantic web languages such as RDF, RDF(S), OWL, DAML + OIL, etc., and these can be studied

through examination of relevant projects, including On-To-Knowledge, European semantic systems initiatives (<http://www.essi-cluster.org/>), SEKT (semantically enabled knowledge technologies, <http://www.sekt-project.com/> and www.sekt.org), DIP (data, information, and process integration with semantic web services), knowledge web (<http://knowledgeweb.semanticweb.org/>); DERI (Digital Enterprise Research Institute – making semantic web real, <http://www.deri.org>), Ontoprise® GmbH (a semantic technologies provider), Triple20 (an RDF/RDF(S)/OWL visualization and editing tool under development at the University of Amsterdam, Human Computer Studies Laboratory), OntoWeb (ontology-based information exchange for knowledge management and electronic commerce), REWERSE (reasoning on the web with rules and semantics), etc. [11, 12].

Third generation (circa 2003–present). Ontology learning and discovery aim at developing methods and tools that decrease the effort for engineering and management of ontologies [11], and include methods and techniques for extracting, building an ontology from scratch, enriching, or adapting an existing ontology in a semi-automatic manner using previously defined sources and thesauri. There are also a few systems for semantic discovery that provide support for semi-automatic extraction of relevant concepts and relations between them from (web) documents and existing ontologies.

The ontology languages are XML(s) (extensible markup language), RDF(s) (resource description framework), OIL (ontology inference layer), DAML + OIL, and OWL (web ontology language), which generally have the foundations in knowledge representation paradigms. Their main role is directed to the development of ontologies. These languages are under research and development by the World Wide Web Consortium (W3C, <http://www.w3c.org>), and constitute the well-known 'pyramid of languages', which is briefly described below [11, 12].

1. *RDF* (resource description framework) is a foundation for processing metadata towards the standardization and use of its descriptions of web-based resources. RDF Schema introduce a more relevant and expressive representation formalism and basic ontological primitives for web resources. RDF(S) is the combination of RDF and RDF Schema. However, these languages are not considered to be powerful ontology languages, but are rather general languages for describing web metadata.
2. *OIL* (ontology interchange language and ontology inference layer) was the first ontology language to combine elements from description logics, frame

languages, and web standards such as XML and RDF.

3. DAML + OIL (DARPA agent markup language + ontology interchange language) define a semantic markup language for web resources. It builds on top of earlier languages such as RDF and RDF(S), and extends these languages with richer modelling primitives.
4. OWL (web ontology language) can be used to represent explicitly the meaning of terms in vocabularies. It has been designed based on the existing languages by the Web Ontology Working Group (<http://www.w3.org/2001/sw/WebOnt/charter>). OWL is also based on DAML + OIL, but different levels of expressivity are included in the language.

Generally, ontology development tools provide the basic support for the ontology population so that ontology developers can create instances with their editors [12]. Annotation support systems facilitate the attachment of RDF descriptions to web pages and other information sources either manually or semi-automatically using techniques from natural language processing. Special-purpose tools and methodologies support the maintenance (merging, alignment, etc.), validation, and evolution of the ontology models in highly complex and dynamic environments.

The application of UML, related models, and profiles provided by the OMG [13] for information and knowledge modelling in collaborative/global enterprises has been approached by research projects carried out at Loughborough University, as described in reference [14]. The role of UML as a conceptual modelling language for ontologies and semantic web has also become an important research topic [12, 15]. Therefore choosing UML as a common modelling approach may be directed to solve interoperability aspects at the stage of enterprise modelling as well as related complex system analysis and design. Falkovych *et al.* [15] argue that UML could be a key modelling approach for overcoming the ontology development bottleneck, especially due to its wide acceptance and sophisticated support tools. UML class diagrams may be employed for representing concepts and axioms using the object constraint language (OCL). Transformation-based approaches and mappings are a promising way of establishing a connection between UML and web-based ontology languages. This research has identified commonalities and differences in the previous approaches and it is also applied for the collaborative networked enterprise engineering.

Moreover, at present there is a request for a proposal within the OMG that attempts to define a suitable modelling approach for semantic web ontology

languages according to the model-driven architecture (MDA) specifications, such as [16–18]:

- (a) OMG should provide an ontology definition metamodel (ODM);
- (b) the definition of a UML profile for ontology building and/or extraction;
- (c) mapping methods between OWL and ODM, ODM and ontology UML profile, and from ontology UML profile to other existing UML profiles.

2.1 Towards an ontology definition metamodel (ODM)

The OMG has defined a profile that supports an ontology design called the ontology UML profile, which is a standard extension of UML and is also based on the meta-object facility (MOF). The ontology UML profile defines the support that a unified ontology modelling approach provides for an ODM. However, UML is based on the object-oriented paradigm and has some limitations regarding ontology development. These limitations can be overcome by using UML's extensions (i.e. UML profiles), as well as other OMG standards and architectural paradigms, such as MDA [15–20]. Currently, there is an initiative (i.e. request for proposal) within the OMG aiming to define a suitable language for semantic web ontology languages in the context of the MDA. The proposed ODM and ontology UML profiles are shown in Fig. 4, and they can be considered as an effort to elaborate standard ontology metamodelling techniques using the ontology mapping facilities. ODM and ontology UML profiles are based on OWL and the concepts can be used as stereotypes in the UML models (similar to any other OMG UML profiles).

Baclavski *et al.* [20] have demonstrated the benefits of using UML and DAML + OIL as follows.

1. UML is used as a modelling method for knowledge representation languages such as DAML.
2. Standard UML models are transformed into OIL or DAML + OIL ontologies.

The first direction arose due to the fact that current ontology representation languages lack representation possibilities such as a graphical front-end. Generally, DAML does not have sufficient tool support, while UML is a commonly accepted graphical notation that can be used to represent DAML ontologies. Furthermore, Table 1 illustrates a high-level mapping between DAML and UML [20].

3 BEYOND RELATED WORK

Many concepts and theories are encompassed in enterprise engineering, since it includes dissimilar

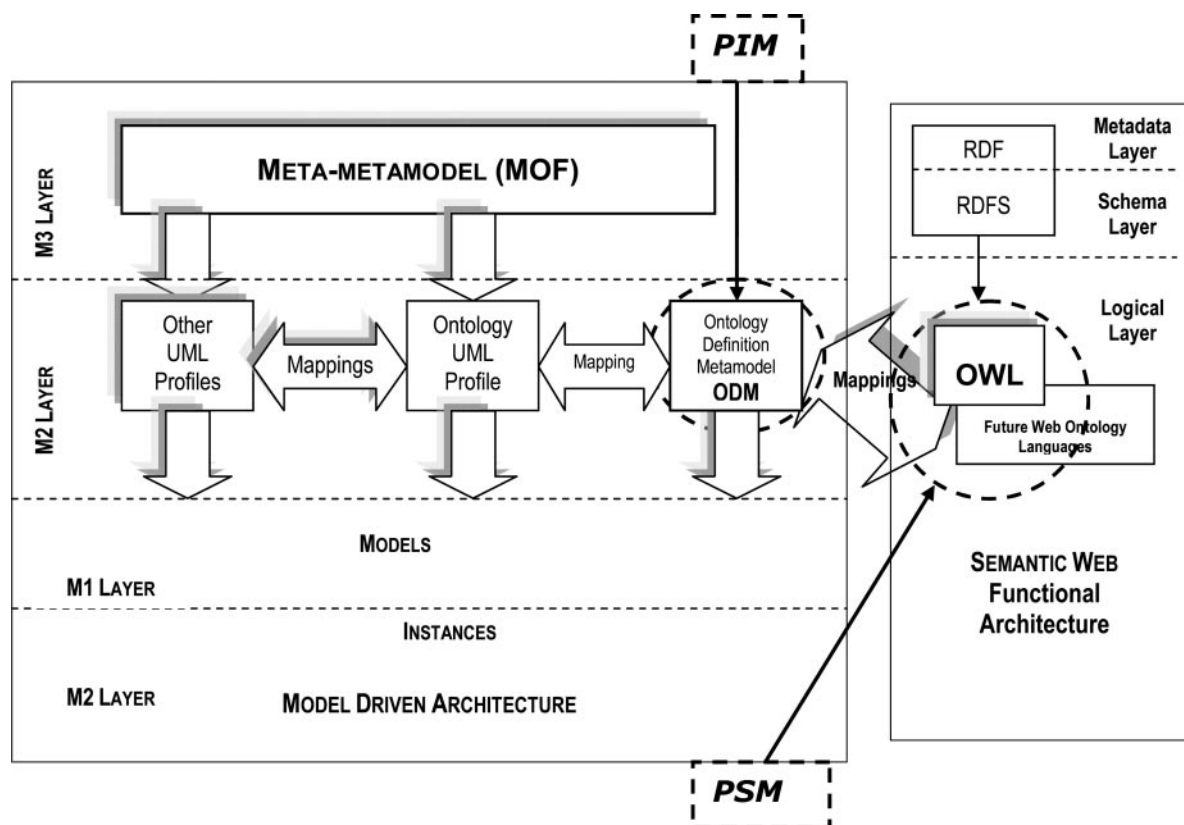


Fig. 4 Ontology definition metamodel [16–18]

Table 1 A mapping between DAML and UML [20]

DAML concepts	UML concepts
Ontology	Package
Class	Class
Hierarchy	Class generalization relation
Properties	Attributes
Restrictions	Constraints
Cardinalities	Multiplicities
Data types	Data types
Instances	Object instances
Values	Attribute values

terminologies as well as complex and abstract entities and representations. Differences exist in syntax, structure, and most importantly in meaning. Therefore, a challenge for the system developer and/or the enterprise information/knowledge modeller is to determine whether differences in naming reflect a deeper underlying difference in concepts and meanings. Differences in naming can be handled relatively simply using readily available tools such as lookup tables or thesauri. Differences in concepts and definitions, however, require a much deeper understanding of the enterprise domains and can be more difficult to capture and formalize.

First, UEML is intended to provide a common enterprise modelling environment, both in terms

of terminology to be used and the structure of concepts to be represented. It is based on a widely accepted metamodel and from which models of particular enterprise systems can be mapped. The kernel of UEML is a set of core constructs that include the following entities (<http://www.ueml.org>) [4].

1. Event (or process triggering condition), which captures the change in the system state.
2. Process, which defines the set of processes, subprocesses, or activities (i.e. elementary steps) that are triggered by one or more event occurrences.
3. Activity, which transforms inputs into outputs over time using the resources.
4. Enterprise object, which is used, processed, transformed, or created by activities carried out during the operations of an enterprise. Enterprise objects and their states are the elements involved in the flows of activities. They are defined by their properties, i.e. attributes for static properties and methods for behavioural properties.
5. Resource, which is a class of enterprise objects used for supporting the execution of processes and activities.
6. Organization unit, which defines an entity of an organization structure provided with authority

and responsibility on identified activities and enterprise objects of the enterprise.

The unification and/or interoperability of some enterprise modelling languages are achieved by a UEML core module, which follows the process specification language (PSL) concept and structure and includes XML interfacing capabilities. This language was developed at the National Institute of Standards and Technology (NIST) and proposes a formal ontology and translation mechanism representing some particular manufacturing concepts [21]. However, this language is based on earlier knowledge sharing and exchange languages such as the knowledge query markup language (KQML), knowledge interchange format (KIF), and foundation for intelligent physical agents (FIPA) standard for agent communication languages (ACL).

Noran [3] has suggested a comprehensive meta-methodology for collaborative networked organizations having several mapping and interoperability capabilities. In consequence, a common ontology model is considered essential for supporting this holistic approach of the architectural frameworks such as CIM-OSA, PERA, ARIS, GRAI-GIM, and ZACHMAN and their mapping especially to GERAM. This approach also includes a comparative analysis of IDEF family tools versus UML from an ontological perspective as IDEF5 captures an ontology description. In addition, an overall assessment and an analytical mapping to GERAM of the architectural framework for command, control, communication, computers, intelligence, surveillance, and reconnaissance (C4ISR) developed by the US Department of Defence (DoD) are dealt with. The C4ISR has been directed to provide the concepts and infrastructures for interoperable information systems and associated metrics for the analysis of the performances of an information system [22]. The C4ISR has also clearly stated that 'architectures should use common and/or standardized terms and definitions'. However, this framework did not intend to define a comprehensive set of terms that must be used in all architectures, but instead it provides a limited set of critical definitions. Some lists and definitions of common terms are included in joint dictionaries and data models such as the universal reference resources and an integrated dictionary for any enterprise architecture, which may be used as thesauri.

The enterprise ontology project carried out at the AIAI University of Edinburgh also defined some concepts and terms that are divided into the following entities: activities, organization, strategy, and marketing [23]. This ontology partially covers extended/virtual enterprise concepts and the related modelling requirements.

Lin [6] and Lin *et al.* [7] have suggested a manufacturing system engineering (MSE) ontological model, which has been slightly refined and applied in this research. This model is shown in Fig. 5 and has a high level of abstraction compared with the previous models such as PSL and STEP (standard for the exchange of product model data). This is illustrated by a top-level representation where a taxonomy of this model has been captured in seven key base classes, project, (work)flow, extended/virtual-enterprise, enterprise, resource, process, and enterprise strategy, using the knowledge and experiences of existing manufacturing system information models [24–26]. These top-level classes are abstract classes, so each represents a hierarchy of subclasses that are detailed and classified according to their main characteristics. Figure 6 presents the section of the MSE class structure and the hierarchy between classes, represented using the ontology editor tool plug-in, Protégé OWL (<http://protege.stanford.edu/plugins/owl/>), and its visualization plug-in, OWLViz (<http://www.co-ode.org/downloads/owlviz/co-ode-index.php>).

The project class represents the business and production objects and related physical items, such as products, or non-physical items, such as documents, contracts, or an information system. The definition of the project class is important as this provides the trigger for the formation and operation of the extended/virtual enterprise project to the MSE process. The MSE ontological model encompasses several independent companies for operation of the networked enterprise. Therefore, the extended/virtual-enterprise class has been defined, which is an aggregation of enterprise classes. Each enterprise class is concerned with the representation of capabilities and information in any specific networked enterprise system, as the processes, resources, and strategies are arranged into different enterprises related to their individual business objectives and functions.

The enterprise class captures how the process is determined and controlled (through links to strategies), and where the process is located, or the area of responsibility where the process takes place (captured by including links to enterprises). The resource class describes the entities and mechanisms that enable a process to be executed. At a high level of abstraction, it could be a human resource or a manufacturing resource; at a lower, more detailed level of abstraction, it could be machinery tools, raw materials, etc. Resources may be represented by various types of information and knowledge, which may include what the resource can do (through links to process), where it is located (through links to enterprises), and how it is allocated (through links to strategy).

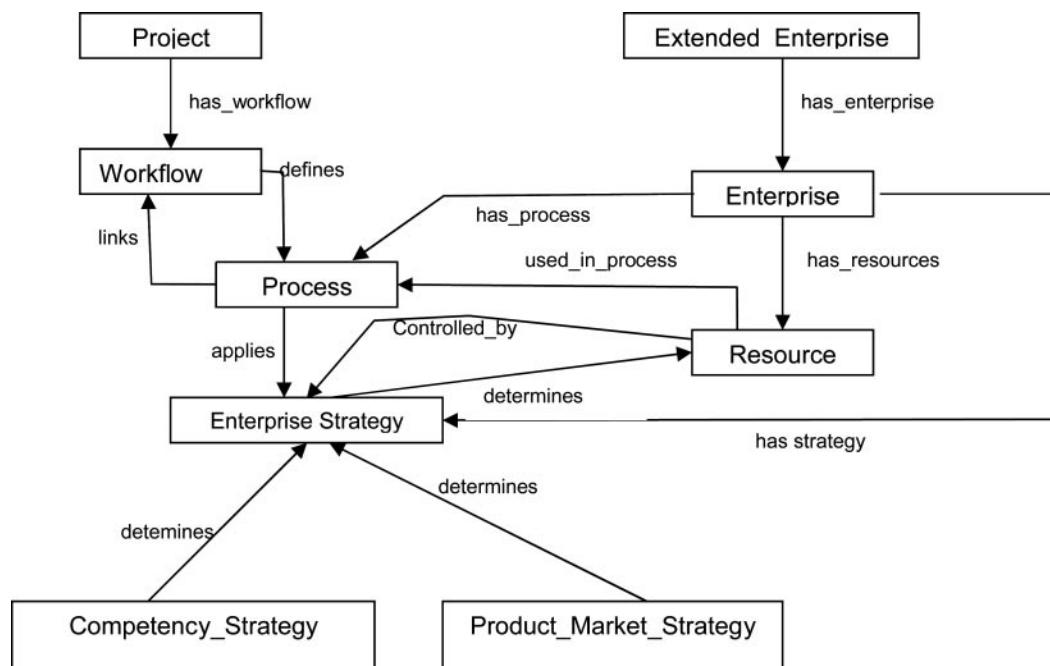


Fig 5 Top-level ontology for virtual/extended enterprise based on Lin [6]

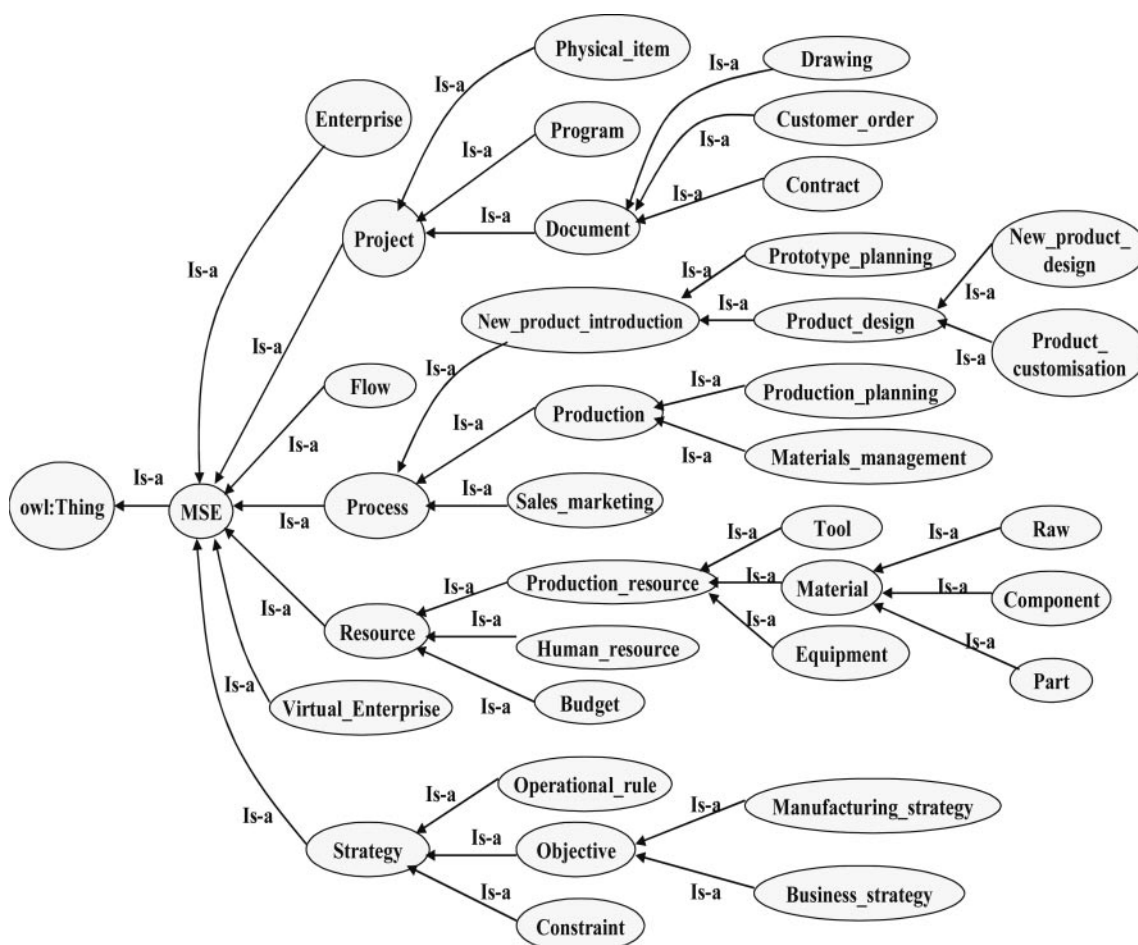


Fig. 6 A manufacturing enterprise system engineering ontological model represented in OWL

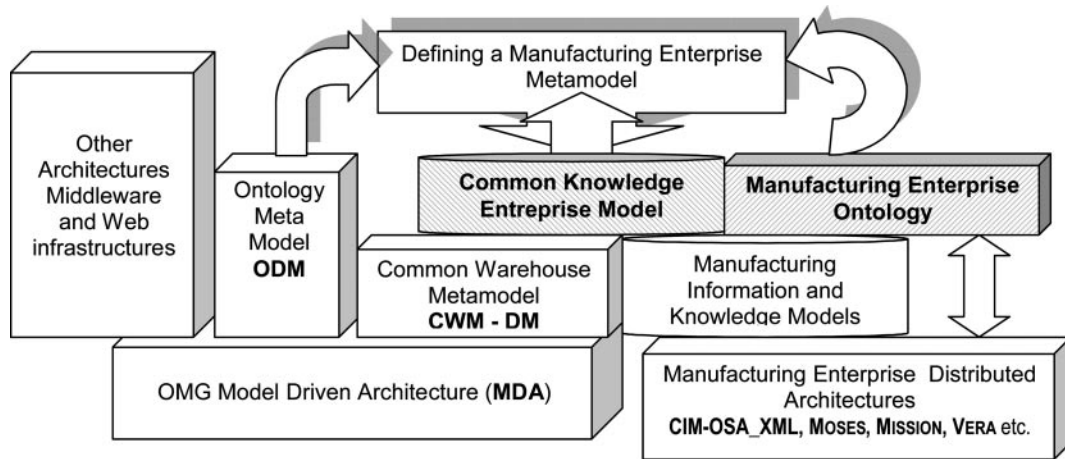


Fig. 7 Architectural infrastructure for the definition of a manufacturing enterprise metamodel

The enterprise strategy class represents the constraints, objectives, heuristics, knowledge, and procedures that contribute to the decision-making process within an enterprise, using its facilities and resources for executing a related process. A company/enterprise strategy may also be described from the following perspectives [27]:

- the product–market strategy, which defines the enterprise as a collection of product/market opportunities;
- the competence-based strategy, which defines a company/enterprise as a collection of resources or competencies;
- integration of the previous two approaches, which define the mission and vision of a manufacturing company/enterprise.

This semantic model enables the information and knowledge sharing and exchanging through different enterprise applications which are underpinned by common ontologies and thesauri. It has been implemented and visualized using plug-ins of the Protégé system, and a detailed description of this manufacturing ontology for global/extended project teams is included in Lin [6].

However, this ontological model does not use any standardized model or profile as, for example, those defined by the OMG and called the ontology meta-model. Neaga [28] and Neaga and Harding [29] have defined a standard common knowledge enterprise model applied to the extended enterprise/virtual enterprise. This model is based on the OMG's common warehouse metamodel (CWM) and incorporates the enterprise knowledge models obtained through discovery techniques and data mining. These techniques have very good potential in intelligent decision-making processing in a collaborative networked enterprise as, for example, business

partners' selection based on their core competencies and past performance analysis, coordination in the distribution of production processes, forecasting of production disfunctionality [30], and process quality control improvement [31].

The architectural infrastructure of the common knowledge enterprise model is shown in Fig. 7. The common knowledge enterprise model has been designed using UML and the common warehouse metamodel for data mining (CWM-DM) [19, 32] as detailed in references [28] and [29]. However, this model lacks a common understanding of manufacturing domain terminologies, and especially concepts usually provided by ontologies and processed by semantic systems. Furthermore, this model may be refined and enriched by semantic discovery, which is mainly directed to find semantic associations in large datasets and web documents associated with enterprise systems, and/or applying clustering techniques for concepts related to a domain such as manufacturing engineering. Therefore a step further in enterprise engineering and modelling approaches is the bidirectional combination between ontological and knowledge discovery systems, which may define a semantic-driven environment/system.

Figure 7 also illustrates an architectural infrastructure for the definition of a manufacturing enterprise metamodel, which takes advantage of the existing enterprise models and ontologies as already recommended by the OMG, especially by the definition of the model-driven architecture (MDA) [19]. One of the main aims of the MDA is to provide an abstract infrastructure in order flexibly to integrate existing systems, models, and services with future related developments. The main strength of the MDA is the separation of the application logic from the technologies such as .Net, CORBA, and/or web services. The

basic idea around the MDA multilayer infrastructure is the development of a platform-independent model (PIM), which maps to one or more platform-specific models (PSM) that can be implemented. These models are usually defined in UML. Also at the core of the MDA is a combination of the UML, meta-object facility (MOF), and common warehouse metamodel (CWM) [19, 32].

4 DEFINING A MANUFACTURING ENTERPRISE METAMODEL

This section describes an (abstract) metamodel that facilitates collaborative networked enterprise engineering supported by an ontological modelling strategy and applied knowledge discovery based on the OMG's common warehouse metamodel. This section suggests the following main directions for defining the manufacturing enterprise metamodel.

1. Transforming the MSE ontology to a UML model.
2. Converting the enterprise models usually represented using UML to OWL models as this transformation approach has been already defined and tested [33–35]. However, enterprise models represented in UML should also be possible to convert to OWL, but this issue has not been considered yet and therefore it is proposed by the research reported in this paper.

Direction 1 includes the following detailed phases:

- (a) applying metamodeling to the MSE ontology proposed by Lin [6] and Lin *et al.* [7];
- (b) using transformation techniques for the conversion of the OWL model to UML, which has been widely used for the definition of a standard common knowledge enterprise model;
- (c) combining the transformed model with the common knowledge enterprise model and producing the manufacturing enterprise metamodel;
- (d) using mapping capabilities of the resulting models.

However, this top-down approach could not be supported by practical examples and development solutions for the following main reasons:

- (a) high level of abstraction;
- (b) the approaches related to ontology metamodeling are still refining their representations;
- (c) semantic technology does not yet provide support for enterprise computing, but there is ongoing research and prototyping modules are under development.

4.1 Applying ontology metamodeling and transformation approaches

A manufacturing enterprise metamodel (ME_M) should comprehend a common and/or standard manufacturing enterprise ontology that captures, represents, and communicates the concepts and theories. It should also provide knowledge in order to support collaborative networked enterprise engineering better. In order to use the graphical capabilities of UML, the ME_M should be described in UML based on some profiles that enable the use of UML diagrams. Other benefits of using UML include the possibility of incorporating existing (meta)models such as the common enterprise model based on knowledge discovered, as fully described in reference [27]. This modelling approach produced the extended enterprise common warehouse metamodel (EE_CWM), which is developed using the OMG's CWM-DM and manufacturing information modelling issues. It is mainly composed of the following diagrams [28, 29, 32].

1. The main model diagram, which represents a high level discovery model that is defined as a generic representation of several input data, enterprise application specifications, and the output generated by the execution of data mining algorithms including knowledge-driven models/entities;
2. The settings diagram, which defines the mining algorithm settings and their usage relationships to the attributes of the input data specification. The mining algorithms that are included are as follows: statistics, clustering, association rule, classification, and regression.
3. The attributes diagram, which describes the mining attributes such as numeric, category, and ordinal.

Dedicated transformations and/or mapping capabilities should be provided between this model, ODM, and OWL. In addition, the EE_CWM may also be represented in XML format [19, 20, 32]. The mapping capabilities are from an ontology UML profile into another, technology-specific, UML profile, and additional transformations can be added to support the usage of ontologies. Incorporating a knowledge-driven model based on discovery techniques enables the semantic discovery of the concepts and theories related to the enterprise engineering, and the integration should also be based on ontologies re-using alignment and merging.

Alternatively, an initial stage of the construction of the ME_M may include the representation in OWL of the manufacturing system engineering (MSE) ontology for the extended enterprise (EE_OWL) as presented in section 3. Generally, an

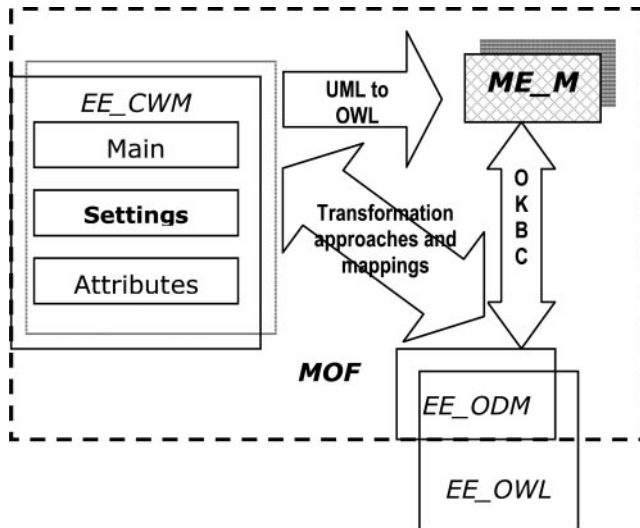


Fig. 8 Towards a manufacturing enterprise metamodel

OWL model may also be represented in XML format [11, 12]. The manufacturing enterprise system ontology could be converted into UML using the open knowledge base connectivity (OKBC), which is described in reference [12]. In order to provide interoperability capabilities between Protégé and UML tools such as Poseidon, Rational Rose, etc., and their corresponding plug-ins have been developed [12, 33, 35].

Although some incompatibilities between UML and OKBC still remain as considered in reference [15], the following transformations may be applied to a manufacturing model fully described in UML, related (meta) models, and profiles.

1. UML classes can be compared and translated to OKBC classes.
2. UML objects are similar to OKBC instances.
3. UML attributes and relationships are comparable to OKBC slots.

UML is usually used for enterprise system analysis, modelling, and design by human experts, and OWL is intended to be employed at run-time. The complementary nature of UML and OWL justify their combination, but their incompatibilities may result in an inability to represent all elements from the ontology representation languages using UML [35]. In order to avoid this issue, a number of extensions to UML have been proposed, such as the profiles and ODM described in section 2.1 and shown in Fig. 4. A metamodel defined using Protégé might also be described in UML. Using transformation techniques it is possible to obtain the metamodel depicted in Fig. 8. It should also be possible to define a so-called EE-ODM (extended enterprise ontology definition metamodel) based on the MSE ontological

model described in OWL. This aspect is also shown in Fig. 8.

On the other hand, Gašević [35] has developed the tool UMLtoOWL, which converts an extended ontology UML profile (OUP) represented in XML metadata interchange (XMI) format to OWL models. The corresponding OWL model is produced as an output in a format suitable to be imported into a dedicated system for ontology development (e.g. Protégé) where it can be further refined.

Despite the existence of a general methodology for transforming UML diagrams, in OWL representations several open issues are under consideration [15–17, 35]. One of the main issues is the difference between the metamodeling according to the MDA and CWM and the metamodeling approach in the framework of semantic web and ontology languages. MDA has four defined layers such as instances, models, metamodels, and profiles, and meta-metamodels defined using MOF [19]. A semantic web architecture may extend its layer structure, especially if it is based on OWL Lite and associated metamodels and primitives [16].

Therefore the ME_M may be defined at the level of MDA as part of MOF and shown in Fig. 8. This section introduces the main aspects and related transformation approaches in order to define a manufacturing enterprise metamodel (ME_M), but its further potential design and implementation solutions could be outlined and inferred.

5 MAIN CONTRIBUTIONS AND FURTHER RESEARCH

The main contribution of this research is the justification and the conceptual definition of the basis of a collaborative networked enterprise metamodel mainly based on ontology and knowledge discovery. The paper presents a novel approach for collaborative networked enterprise engineering supported by an ontological metamodeling strategy, semantic web technologies, and applied knowledge discovery based on the OMG's common warehouse metamodel. Furthermore, the combination between ontology modelling and knowledge discovery is relatively new from a knowledge and ontology engineering perspective. This approach also demonstrates that the existing models and architectures such as CWM, ODM, and MDA could be successfully applied to the extended/virtual manufacturing enterprise. The benefits of the unified semantic approach suggested in this paper are directed at contributing to the enterprise systems interoperability and related issues such as legacy systems. The proposed model is designed using UML for the semantic web and some implementations based on semantic support

languages will be provided in further research. It is also suggested that the enterprise models represented in UEML can be converted to ontological models through appropriate transformation techniques, which have not yet been addressed by previous research.

6 CONCLUDING REMARKS

The semantic-driven framework and the conceptual defined manufacturing enterprise metamodel encompass both knowledge discovery and ontology models, being directed to applying semantic discovery for enterprise engineering concepts and theories. Further refinement of the model and especially its developments based on the latest emerging semantic web technologies will enhance the approach included in this paper and its application at a particular level. Furthermore, this approach is the result of existing trends of working W3C and OMG closely together in order to define and develop highly performant metamodels and standards that will bridge the gap between academia and industry regarding semantic web research.

REFERENCES

- 1 Tolle, M. *Management and engineering of virtual enterprises*. PhD Thesis, Department of Manufacturing Engineering and Management, Technical University of Denmark, 2004.
- 2 Bernus, P., Nemes, L., and Schmidt, G. (eds) *Handbook on enterprise architecture*, Springer Series on International Handbooks on Information Systems, 2003 (Springer-Verlag, Berlin).
- 3 Noran, O. *A meta-methodology for collaborative networked organizations*. PhD Thesis, School of Computing and Information Technology, Griffith University, Brisbane, Australia, 2004.
- 4 Vernadat, F. B. UEML: towards a unified enterprise modelling language. *Int. J. Prod. Res.*, 2002, **40**(17), 4309–4321.
- 5 Stark, J. *Product lifecycle management: 21st century paradigm for product realisation*, 2005 (Springer Verlag, London); also <http://mars.jpl.nasa.gov/msp98/orbiter/>, last access October 2006.
- 6 Lin, H. K. *Manufacturing system engineering ontology model for global extended project team*. PhD Thesis, Loughborough University, 2004.
- 7 Lin, H. K., Harding, J. A., and Shahbaz, M. Manufacturing system engineering ontology for semantic interoperability across extended project teams. *Int. J. Prod. Res.*, 2004, **42**(24), 5099–5118.
- 8 Rumbaugh, J., Jacobson, I., and Booch, G. *The unified modeling language, reference manual*, 1999 (Addison-Wesley, Reading, Massachusetts).
- 9 FP6 Integrated Project: advanced technologies for interoperability of heterogeneous enterprise networks and their applications, ATHENA; <http://www.athena-ip.org/>, last access May 2005.
- 10 INTEROP FP6 Network of Excellence: Interoperability Research for Networked Enterprises Applications and Software (INTEROP), 2004; <http://www.interop-noe.org/>, last access August 2005.
- 11 Staab, S. and Studer, R. (eds) *Handbook on ontologies*, 2004 (Springer-Verlag, Berlin).
- 12 Gomez-Perez, A., Lopez, M. F., and Corcho, O. *Ontological engineering with examples from areas of knowledge management, e-commerce and semantic web*, 2004 (Springer-Verlag, Berlin).
- 13 OMG – Object Management Group. Overview at <http://www.omg.org>, last access April 2005.
- 14 Zhao, J., Cheung, W. M., and Young, R. I. M. A consistent manufacturing data model to support virtual enterprises. *Int. J. Agile Managmt Systems*, 1999, **1**(3), 150–158.
- 15 Falkovych, K., Sabou, M., and Stuckenschmidt, H. UML for the semantic web: transformation-based approaches, Ongoing research at the Department of Multimedia and Human Computer Interaction, CWI, and Artificial Intelligence Department, Vrije Universiteit, Amsterdam, The Netherlands, 2005.
- 16 Djuric, D., Gašević, D., and Devedžić, V. Ontology modelling and MDA. *J. Object Technol.*, 2005, **4**(1), 110–128.
- 17 Djuric, D. MDA-based ontology infrastructure. *Computer Sci. Information Systems (ComSIS)*, 2004, **1**(1), 91–116; <http://www.comsis.fon.bg.ac.yu/ComSISpdf/Volume01/Papers/DraganDjuric.pdf>, last access October 2006.
- 18 OMG ODM RFP. Ontology definition metamodel request for proposal. OMG Document ad/2003-03-40, <http://www.omg.org/cgi-bin/doc?ad/2003-03-40>, 2003, last access May 2005.
- 19 OMG MDA RFP. Model-driven architecture (MDA). Document ormsc/2001-07-01, Architecture Board ORMSC, 2001.
- 20 Baclavski, K., Kokar, M. K., Kogut, P. A., et al. Extending the unified modelling language for ontology development. Technical report of Contract F 30602-00-C-0188, Air Force Research Laboratory, USA, 2005.
- 21 Pouchard, L., Ivezic, N., and Schlenoff, C. Ontology engineering for distributed collaboration in manufacturing. NIST Document, 2004.
- 22 Noran, O. A systematic evaluation of the C4ISR AF using ISO15704 Annex A (GERAM). *Computers in Industry*, 2005, **56**, 407–427.
- 23 Uschold, M., King, M., Moralee, S., and Zorgios, Y. The enterprise ontology. KER Revised Complete Draft, AAAI, The University of Edinburgh, 1997.
- 24 Harding, J. A. and Yu, B. Information-centred enterprise design supported by a factory data model and data warehousing. *Computers in Industry*, 1999, **40**, 23–36.
- 25 Kosanke, K., Vernadat, F., and Zelm, M. CIMOSA: enterprise engineering and integration. *Computers in Industry*, 1999, **40**, 83–97.

- 26 **Molina, A.** and **Bell, R.** A manufacturing model representation of a flexible manufacturing facility. *Proc. Instn Mech. Engrs, Part B: J. Engineering Manufacture*, 1999, **213**(B3), 225–246.
- 27 **Drejer, A.** *Strategic management and core competencies, theory and application*, 2002 (Quorum Books, London).
- 28 **Neaga, E. I.** *Framework for distributed knowledge discovery systems embedded in extended enterprise*. PhD Thesis, Loughborough University, 2003.
- 29 **Neaga, E. I.** and **Harding, J. A.** An enterprise modeling and integration framework based on knowledge discovery and data mining. *Int. J. Prod. Res.*, 2005, **43**(6), 1089–1108.
- 30 **Lau, H. C. W., Chin, K. S., Pun, K. F., and Ning, A.** Decision supporting functionality in a virtual enterprise network. *Expert Systems with Applics*, 2000, **19**, 261–270.
- 31 **Shahbaz, M.** and **Harding, J. A.** An integrated data mining model for a manufacturing enterprise. In *Advances in manufacturing technology XVII* (Eds Y. Qin and N. Juster), Proceedings of the International Conference on Manufacturing Research, Strathclyde, 2003, pp. 539–545 (Professional Engineering Publishing Ltd, Bury St Edmunds and London).
- 32 **Poole, J., Chang, D., Tolbert, D., and Mellor, D.** *Common warehouse metamodel: an introduction to the standard for data warehouse integration*, 2002 (OMG Press, John Wiley, New York).
- 33 Protégé and UML, <http://protege.stanford.edu/>, <http://protege.stanford.edu/plugins/uml/>, last access May 2005.
- 34 **Knublauch, H.** Case study: using Protégé to convert the travel ontology to UML and OWL. In Proceedings of the 2nd International Workshop on *Evaluation of ontology-based tools* (eds Y. Sure and O. Corcho), held at the 2nd International Semantic Web Conference (ISWC), Florida, USA, 2003, on-line at <http://sunsite.informatik.rwth-aachen.de/Publications/CEUR-WS/Vol-87/>, last access May 2005.
- 35 **Gašević, D.** UML to OWL: converter from UML to OWL at <http://www.sfu.ca/~dgasevic/projects/UMLtoOWL/>, last access May 2005.