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Building an Ontology for Intelligent Maintenance Systems and Spare Parts Supply Chain Integration

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Abstract: Global competition has been leading to more complex production systems, in which satisfactory maintenance is crucial for the operations. The ability to properly forecast failures, provided by Intelligent Maintenance Systems (IMS) can avoid downtimes and provide a competitive advantage. Moreover, it can also enable more precise demand planning in Spare Parts Supply Chain (SPSC), resulting in the availability of parts and services when they are necessary in shop floor, avoiding breakdowns and production interruptions. The proper integration of IMS and SPSC is of utmost importance to achieve these results. Some of the challenges related to this integration refer to semantic differences between these areas with diverse concepts and vocabulary. This work intends to propose the building of an ontology to overcome these difficulties by providing a common vocabulary and proper semantic integration of the areas, as a basis for the construction of a future integration information system to integrate IMS and SPSC.

1. INTRODUCTION

When considering diverse areas suchlike IMS and SPSC, the definition of a common vocabulary and a set of concepts and relations is necessary in order to enable the achievement of all benefits aforementioned. The existence of an ontology provides a common vocabulary to be used by the actors from both areas, besides enabling a better understanding of the effects each entity provokes on the other and making the construction of an integration information system easier.

According to (Guizzardi, 2005), the term ontology was coined in the 17th century in philosophy area. Ontologies have thus origins in the field of Philosophy, where it means a systematic explanation of existence (Gómez-Pérez and Benjamins, 1999) or a "theory of existence" (Mizoguchi, 2003). In the Information Systems field, an ontology can be described as a "specification of a representational vocabulary for a shared domain of discourse — definitions of classes, relations, functions, and other objects" (Gruber, 1993). It defines a "common vocabulary for researchers who need to share information in a domain" (Noy and McGuinness, 2001). As pointed out in (Noy and McGuinness, 2001), some of the reasons for this growing usage of ontology in this field reside in some important benefits in its usage such as: (i) to share common understanding of the structure of information among people or software agents; (ii) to enable reuse of domain knowledge to make domain assumptions explicit; (iii) to separate domain knowledge from operation knowledge.

Therefore, we believe the existence of an ontology to model the integration between IMS and SPSC is the first step to accomplish all the objectives of such integration. In this work, we are going to present the steps followed to build an integration ontology. This paper is organized in the following topics: a state-of-the-art analysis, a description of the ontology building approach and the ontology concepts and the study case development used to validate the ontology. At the end, a conclusion session.

2. STATE-OF-THE-ART ANALYSIS

2.1 IMS

IMS refers to systems or services capable of monitoring the state of degradation of a device in order to make possible preventive actions to avoid production losses. Many researches propose approaches to perform this task, and one of the most important is called Watchdog Agent (Djurdjanovic et al., 2003). It consists in a set of algorithms used to evaluate sensor outputs to predict failures and evaluate the working state of a device.

2.2 Manufacturing ontologies

Many works have been developed proposing an ontology in the domain of manufacturing. The work of (Pouchard et al., 2000) presents an ontology-based approach for distributed collaboration in manufacturing, aiming interoperability and translation mechanisms representing manufacturing concepts. These concepts are represented through an ontology built upon PSL (*Process Specification Language*) composed by three basic entities: activity, object and timepoint and four basic relations: participates_in, before, begin_of and end_of. The paper also describes how concepts and relations are represented in PSL, but does not describe the actual manufacturing model.

P-PSO ontology (*Politecnico di Milano–Production Systems Ontology*) (Garetti and Fumagalli, 2012) is a structured representation of manufacturing domain, relying on UML (*Unified Modelling Language*) to provide its semantic representation. The addressed aspects are organized in (i) *Physical aspects*, meaning material definition of the system, including equipment, workers and facilities; (ii) *Technological aspects*, defining the transformational view of the system, including the transformational processes that happen in the manufacturing system; and (iii) *Control aspects*, defining the management cycle, including planning, scheduling and control activities. The authors suggest some use examples, such as information exchange, design activity and control activity. A validation was made through its use in robotic areas in automotive manufacturing environment.

MSDL (*Manufacturing Service Description Language*) (Ameri et al., 2012) is an ontology developed to represent manufacturing services, in a formal way, mainly focused in mechanical machining domain. It also describes the extension of MSDL to include metal casting and an interesting general methodology for ontology extension. Its original purpose was "serve as ontology language of an agent-based framework for supply chain deployment". It is decomposed in five level of abstraction. Supplier-level describes the capabilities of a supplier running a manufacturing facility, such as expertise, skills, industry and product focus. Shop-level "describes the system-level capabilities of a manufacturing system owned by a supplier and described the system through its layout and material handling system and other supporting systems such as production planning and inventory control". Machine-level characterizes machines involved in the transformation of raw material into goods. Device-level deals with the characterization of devices, which are considered the lowest level in the hierarchy of physical resources in manufacturing system. Capabilities of machines involved in manufacturing can be inferred through the aggregation of devices. Process-level describes manufacturing processes. Some of the core classes MSDL proposes are Service class to describe services provided by manufacturing providers and consumed by consumers, a SupplierProfile and RFQ (*Request for Proposal*) classes represent demand and supply, with SupplierProfile having two main components: Supplier and ManufacturingServices that the supplier provides. It is an interesting focus, due to the service character of the manufacturing modelling. MSDL also relies on SWRL (*Semantic Web Rule Language*) to constraint concepts by creating complex rules that, in combination with OWL, provides a powerful and up-to-date semantic formalism.

MASON (*Manufacturing Semantic ONtology*) was proposed by (Lemaignan et al., 2006) as an upper-ontology for the manufacturing domain, to be used as a base for more domain-specific ontologies. This work is related to the work of (Pouchard et al., 2000), but relies on up-to-date formalisms (OWL semantics). It also uses SWRL which provides means to specify more complex rules. It is built upon three concepts:

- *Entities*: which provides concepts to specify the product, giving an abstract view of it, like geometric characteristics, material and costs;
- *Operations*: used to describe processes linked to manufacturing, like manufacturing human and launching operations. An interesting point is that is also includes logistic operations in the context of manufacturing;
- *Resources*: stand for resources used, and linked to, manufacturing. For example, machine tools, tools, human resources and geographic resources like plant, workshops, inventories and so forth.

One key point on MASON is that it was designed to be an upper-ontology, not specifically tied to a specific domain in manufacturing. However, it also lacks some expressivity concerning service modelling.

2.3 Maintenance ontologies

Some efforts were made to formalize maintenance in software development area, but there are no significant work specifically on maintenance in manufacturing. However, in the last couple of decades, research in the area of CBM (*Condition-Based Maintenance*) has been performed. CBM relies on the analysis of the environment and the device to evaluate deterioration in a machine and perform maintenance routines based on this analysis. CBM differs from traditional maintenance because "maintenance actions are based on the need of the machinery" (Fumagalli et al., 2010). From this perspective, the work of (Emmanouilidis et al., 2010) points to the importance to develop a domain ontology in the context of CBM to structure knowledge and data relevant to diagnosis task, but with no actual ontology proposition.

However, an important concept related to this work is the concept of failure. Ultimately, a failure or its possibility is what drives the actions from manufacturing shop floor to spare parts supply chain. Its effects and analysis, as well as a proper traceability to parts and root-causes are of high importance in the context of a proper integration between all entities involved in this work. A systematic technique for failure analysis called Failure Mode and Effects Analysis (FMEA) was first proposed by NASA (Ebrahimipour et al., 2010) to analyse system safety and reliability in a systematic way. It provides a framework to understand and classify many characteristics of failure events, including all systems, sub-systems and parts involved, severity, effects and root-cause. It provides a set of concepts that cover a wide range of useful characteristics of a failure event. Some of these concepts are shown in Table 1 (Langford, 1995).

Other works were also good precursors for integrated information modelling regarding maintenance, CBM and operations, like MIMOSA for use in condition monitoring systems (Mathew et al., 2006).

Table 1. FMEA concepts

Concept	Meaning
Failure	Loss of a function.
Failure Mode	Specific way a failure occurs, e.g., the loose of electric contact.

Failure Cause	Cause(s) that lead to the failure. Could be, for example, improper adjustment of electric contacts.
Failure Effect	Consequences of a failure in operation.
Severity	Depends on the ultimate consequences of a failure.
Remarks/Actions	Mitigation proposal to lower or justify a risk level or scenario.

Some works were proposed to describe FMEA knowledge using ontologies. (Zhao and Zhu, 2010) presents an UML-based model to represent FMEA knowledge in which a failure mode related to a part or a process has the following characteristics, based on the original FMEA concepts: Reason, Severity, Occurrence, Detection, Result, Solution.

(Koji et al., 2005) proposed to combine an "extended functional ontology" to a FMEA ontology in order to deal with functions and design flaws unintended by product designers. (Lee, 2001) presents a framework called DAEDALUS, aimed to deal with issues encountered in integrating FMEA and diagnosis models.

2.4 Supply chain ontologies

A number of supply chain ontologies were examined, beginning with those described by (Grubic and Fan, 2010). Enterprise Ontology (EO) is an attempt to model the knowledge of an enterprise, being the basis for more specialized works. It was developed as part of the Enterprise Project in University of Edinburgh to analyse the use of ontology in enterprise modelling. Its purposes are (i) enhance communication between humans, (ii) provide a basis for specifying applications and (iii) support interoperability. It proposes five sections: meta-ontology and time; activity, plan, capability and resource; organization; strategy; and marketing. It is not actually specifically related to supply chain area, despite the fact some of its concepts could be adapted to supply chain modelling.

TOVE Ontologies (acronym of TOronto Virtual Enterprise) (Fadel et al., 1994) is a set of ontologies comprising resource ontology, cost ontology, organization ontology, product ontology, activity-state-time ontology and quality management ontology. It aims to captures the infrastructure of an enterprise. Some of the ontologies reflect a perspective more close to a supply chain, namely resource, organization and activity-state-time ontology. It was implemented on top of a C++ tool and third-party tools for knowledge representation and axioms implementation.

The SCOR model (Supply Chain Operations Reference model) is used in the work of (Fayez et al., 2005) to propose an ontology for supply chain simulation. According to the model, it is organizes in the processes Plan, Source, Make, Deliver, and Return. The SCOR management processes are still decomposed into other three levels of details. The SCOR model was used as the core for the ontology, and two other layers were added. The second layer was called middle ontology, aiming to "explicitly and formally define all the concepts extracted from the different supply chain views". The third layer was called dynamic ontology, aiming to feature the capability to adapt to specific situations and supply chain configurations.

A supply chain ontology (SCO) was proposed by (Ye et al., 2008) aiming to provide the semantic integration and interoperability across applications of supply chain members, acting as an "interlingua" for the application integration architecture. SCOR model is used again as a basis for the knowledge modelling. The model of (Uschold et al., 1998) is followed for the ontology construction which includes four stages: identify the purpose of the ontology; build the ontology; evaluate it; and document it. It claims to be extensible, to support additional information and semantics of specific application domains. The top level classes are Supply_Chain, SC_Structure, Party, Role, Purpose, Activity, Resource, Transfer_Object, Performance, and Performance_Metric. SC_Structure refers to a set of structures that represent supplier-buyers relations within the supply chain. Party is a legal entity that is part of a supply chain. According to the authors, "each party is a downstream entity or an upstream entity of other parties in the chain and plays different roles, such as Supplier, Manufacturer, Retailer, Forwarder, Vendor and Customer, in terms of its capacity and purpose". Purpose refers to the knowledge that affects supply chain management decisions and its configuration and it is specializes into the subclasses Objective and Strategy. Activity is something that must be done and requires and amount of resource. Resource represents a support mechanism for activities. The Transfer_Object "describes a set of business objects that flow through activities in supply chains", while "Performance class represents achievements that entities obtain through activities". The Performance_Metric class refers to the measurement of performance attributes in supply chain. Despite the fact the ontology is partially listed in the paper, the listing does not allow the usage of the ontology and it was not found available in any other place.

Due to alleged weaknesses in SCOR model, (Zdravković et al., 2011) proposed an approach for formalizing supply chain operations overcoming such problems by using ontologies to extend the model and address its main problems, aiming semantic interoperability of its participants and contributing to further enhancement of the reference model. This approach is demonstrated by developing semantically aligned models of the implicit knowledge on the supply chain operations (SCOR reference), called SCOR-KOS (SCOR Knowledge Organization System), problem domain, called SCOR-Cfg for process configuration and, finally, a micro theory for supply chain operations, called SCOR-Full, which semantically enriches the SCOR model.

A very interesting approach is presented by (Jian and Jianyuan, 2011) for the creation of a hierarchical ontology for supply chain. Starting from the reuse of classical ontologies such as TOVE, and considering SCOR model, the authors propose a hierarchy composed of three main layers: meta ontology layer, domain ontology layer and application ontology/instance layer. Meta ontology is composed by representation ontology and upper ontology. Domain ontology includes a generic enterprise ontology, a SCOR ontology and an industrial supply chain ontology. At the lower level, detailed concepts for internal use are provided, and instances and an example based on the food industry.

3. INTEGRATION ONTOLOGY DEVELOPMENT

3.1 Development approach

The work of (Holsapple and Joshi, 2002) proposes five approaches to ontology design, shown in Table 2.

Table 2. Design approaches

Approach	Description
Inspirational	The ontology developer starts with the reason the ontology is needed and uses his/her own knowledge, creativity and personal view on the domain of interest to meet the recognized need.
Inductive	The ontology is developed by the observation of a specific case in the domain of interest and its generalization to other cases in the same domain.
Deductive	In this approach, some general principles are adopted and adaptively applied to build an ontology oriented to a specific case.
Synthetic	The developer identifies a set of base ontologies which serve as base for an unified resulting ontology.
Collaborative	Development is a joint effort of a team of people who share different views and opinions to cooperate in the construction of the ontology.

In the context of this work, we chose to use inspirational, synthetic and collaborative approach. Inspirational because a significant part of the work, specially its first versions are developed through individual work and research from the author. Synthetic due to the strategy of build an ontology upon previous works, as further detailed in the next paragraphs. Finally, collaborative due to the context on which this work is being developed, in an international project with partners and experts from different areas evaluating and contributing to the result.

3.2 Multi-layered design

Based on the approach from (Jian and Jianyuan, 2011), we propose a multi-layered ontology. Among the benefits of this approach is the reuse of existent, consistent and widely accepted upper and domain ontologies, increasing the adoptability and consistency of the model we propose. In addition, more flexibility is obtained by defining the lower layer as the place where specifics on each case are defined. The multi-layered design is shown in the Figure 1.

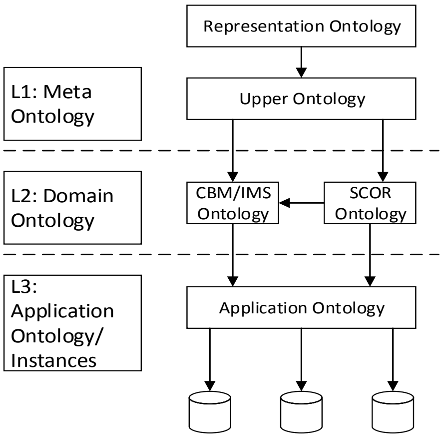


Figure 1. Multi layered design. (Jian and Jianyuan, 2011)

The first layer, Meta Ontology, includes representation and upper ontology. Representation describes what ontology is, its attributes and relationships. Upper ontology represents common sense knowledge, not related to a specific domain.

The Domain Ontology layer describes professional terms for supply chain and CBM/IMS particularly. Semantically speaking, its purpose is to specify with more details what is conceptualized by the upper ontology, based on the considered domains. In this case, we consider IMS, CBM and spare parts supply chain as the domains to be modelled.

Finally, Application Ontology/Instances layer contains concepts related to specific business cases, as well as instances of concepts also related to specific cases. This approach allows enough flexibility to adapt the model to specifics of each kind of enterprise, which would not be feasible to do if trying to concept every concept of all kinds of business.

3.3 Meta ontology layer

In this layer, MASON was chosen due to the simplicity and easiness to match its three mains concepts (Entity, Resource and Operations) to the concepts related to lower layers. This way, all other concepts reside in lower layers but are derived from these three layers. For example, MASON already contains the Part concept, which is taken as basis and further improved at CBM/IMS ontology.

3.4 Domain ontology layer

The CBM/IMS ontology enhances upper layer's Part concept, by adding relations to other Parts in a way based on Composite Design Pattern (Gamma et al., 1995). The following main concepts were also added:

- IMS: indicating the service of analysing Physical Variables in order to define Degradation and forecast failure. It uses a Monitoring Strategy (such as wavelets analysis) and a Monitoring Technique (such as oil analysis, thermography, …) to perform this task.

- Degradation: defines the current state of performance of a given device and its level can trigger maintenance actions and changes in usage level. Others surround this concept like Failure Effect, Failure Mode, Next Failure Level (that allows the establishment of a failure chain). In addition, Failure Probability Function and Failure Probable Date are included.

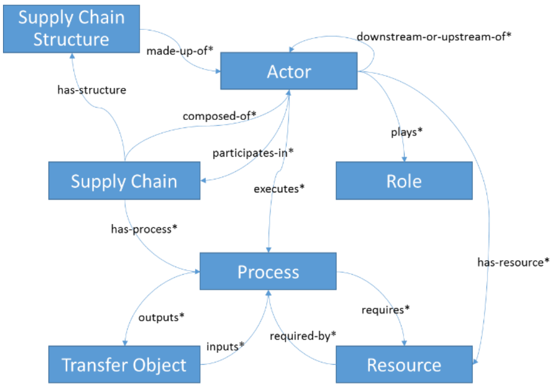
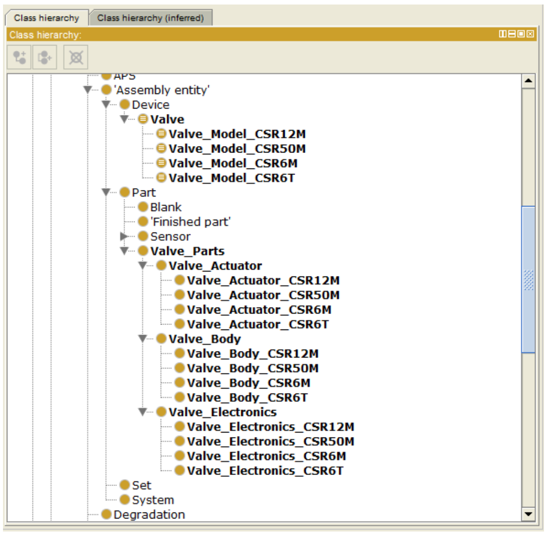


Figure 2. SC ontology main concepts and relations

The Supply Chain ontology is based on the work of (Ye et al., 2008), and has seven main concepts: Supply chain, Supply chain structure, Actor, Role, Process, Resource and Transfer Object. Supply chain refers to the supply chain itself, while Supply Chain structure describes the structure type of SC, having dyadic, serial, divergent, convergent and networked as options. Actor encompasses at least suppliers, manufacturer, logistic service providers, maintenance service providers and customers. Roles are related to the nature of actors, like supplier and customer. Process are used in planning activities within the supply chain. Resources are those entities needed in SC activities to generate transfer objects, i.e., inputs and outputs of SC. The main concepts of SC ontology are shown in Figure 2.



- APS
- 'Assembly entity'
  - Device
    - **Valve**
      - **Valve_Model_CSR12M**
      - **Valve_Model_CSR50M**
      - **Valve_Model_CSR6M**
      - **Valve_Model_CSR6T**
  - Part
    - Blank
    - 'Finished part'
    - Sensor
    - **Valve_Parts**
      - **Valve_Actuator**
        - **Valve_Actuator_CSR12M**
        - **Valve_Actuator_CSR50M**
        - **Valve_Actuator_CSR6M**
        - **Valve_Actuator_CSR6T**
      - **Valve_Body**
        - **Valve_Body_CSR12M**
        - **Valve_Body_CSR50M**
        - **Valve_Body_CSR6M**
        - **Valve_Body_CSR6T**
      - **Valve_Electronics**
        - **Valve_Electronics_CSR12M**
        - **Valve_Electronics_CSR50M**
        - **Valve_Electronics_CSR6M**
        - **Valve_Electronics_CSR6T**
  - Set
  - System
- Degradation

Figure 3. Valve manufacturing specific concepts

3.5 Application/Instantiation layer

This is the layer where specific details are conceptualized, for each industry area. As it would not be possible to exaustivelly model all areas within all possible domain in which this integration is necessary, any specifics shall be added in this layer. Additionally, when modelling not only the specific concepts of a given (sub)domain, but also a real case, instances, or realization of concepts, shall be also created in this layer.

4. VALIDATION

For validation purposes, a study case was developed using a valve manufacturing company and defining the specific concepts related to this company, as shown in Figure 3. After the definition of these concepts, instances of them were created, allowing a detailed understanding of the relations between each specific valve and the spare parts supply chain related to this industry. In this given example, a specific device was modelled as Valve, being composed by three parts (Actuator, Body and Electronics), and also different models of valves. The real valves were also represented by instances of valve concepts, as well as the composition of the supply chain. This approach demonstrates on how real cases can be modelled using detailing of upper layer concepts in application/instantiation layer.

5. CONCLUSIONS

Integration is a key topic in the use of IMS to forecast demand in a SPSC. In addition to the need of building a proper system, the existence of a common vocabulary is critical to achieve a proper integration. This work proposes this vocabulary by presenting an ontology that is used to derive an integration architecture for the integration of IMS and SPSC. A valve manufacturing study case was used to test the validity of the proposals.

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