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Application potentials for an ontology-based integration of intelligent maintenance systems and spare parts supply chain planning

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Abstract

In today's evermore complex manufacturing systems, effective and efficient maintenance has become crucial for achieving operational competitive advantages. Breakdowns and system failures caused by insufficient maintenance can lead to significant economic impact such as higher costs, diminishing profits and declined customer satisfaction. In order to avoid unforeseen systems' unavailability, it is necessary to accurately and precisely forecast maintenance demand in advance – including the provision of maintenance services and spare parts. Moreover, the management and planning of spare parts supply chains has become more important in order to ensure the availability of spare parts and maintenance personnel at the required location and time while operating at reasonable costs. Both issues are recently targeted by the research domains of intelligent maintenance systems (IMS) – forecasting machine failures using a condition-based maintenance (CBM) approach – and spare parts supply chains (SPSC) – planning and providing related maintenance services and spare parts. A proper integration of these two domains enables the exchange of relevant information that could be applied for advanced failure forecasting, machine control and SPSC planning. However, the challenge of integrating both domains is to deal with the different meanings and knowledge, e.g., the concepts being applied in both domains vary in their level of granularity and importance. This paper addresses the integration problem of IMS devices and SPSC planning systems by presenting a refined ontology including concepts that semantically connect the different systems and thus provides the basis for a conceptual integration architecture and a deduced service-oriented architecture facilitating dynamic communication services to support the information exchange. Furthermore, the applied design of the ontology is described for an industrial case and the application potentials to be achieved by the integration of both system types are highlighted.

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Keywords: Integration ontology,Intelligent maintenance systems,Spare parts supply chain

1. Introduction

The management and planning of spare parts supply chains (SPSC) has become a crucial task. In the interest of efficiently planning machine maintenance services and spare parts demand, accurate machine failure forecasts are required. This activity is captured by research in the field of intelligent maintenance systems (IMS). In order to identify prospective maintenance requirements condition-monitoring data is analyzed by assessing sensor information, following the concept of condition based maintenance (CBM). Obtained results are subsequently used for the planning of spare parts supply chains.

The original concept of ontologies, the study of the kind of things that exist, derives from philosophy [1]. Its application in Information Science targets the specification of knowledge aiming at the definition of common semantics and vocabulary within a specific domain. Ontologies support interoperability between different systems by deducing components as well as linking relations [2]. In the context of integrating IMS devices and SCSP systems ontologies depict an effective approach to model both domains including components at different levels of abstraction. This paper refines the ontology presented in

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previous works [3] and [4] and focuses on the exchange of information between different actors, identification of the systems involved and proposes a service-oriented architecture.

The structure of the paper is as follows: Section 2 presents a state-of-the-art analysis covering ontologies, service-oriented architectures as well as open interfaces for data exchange. In section 3 a requirement analysis is conducted, including SPSC planning systems, IMS capabilities and the identification of concepts for information exchange. Section 4 identifies a solution approach by developing an integration ontology and service-oriented architecture.

2. State-of-the-art analysis

2.1. Ontology

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” [5]. It defines a “common vocabulary for researchers who need to share information in a domain” [6]. The growing usage of ontology is due to the benefits in its usage, as sharing common understanding of the structure of information among people or software agents, reuse of domain knowledge to make domain assumptions explicit and to separate domain knowledge from operation knowledge.

Many works have been developed proposing ontologies in the domain of manufacturing. The work of Pouchard [7] presents an ontology-based approach for distributed collaboration in manufacturing, aiming at interoperability and translation mechanisms representing manufacturing concepts. The P-PSO ontology (Politecnico di Milano–Production Systems Ontology) [8] is a structured representation of the manufacturing domain, relying on UML (Unified Modelling Language) to provide its semantic representation. The addressed aspects are organized in physical aspects, technological aspects and control aspects.

MASON (Manufacturing Semantic Ontology) was proposed by Lemaignan [9] as a generic upper-ontology for the manufacturing domain and to be used as a basis for more domain-specific ontologies. This work is related to the work of Pouchard, but relies on up-to-date formalisms (Web Ontology Language semantics). It is built upon three concepts:

- Entities: provide concepts to specify products, e.g. abstract properties 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 it 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 of MASON is that it was designed to be an upper-ontology, not especially tied to a specific domain in manufacturing. However, it also lacks some expressivity concerning service modelling.

Some efforts were made to formalize maintenance in software development areas, but there are no significant works, specifically for maintenance in manufacturing. However, in the last couple of decades, the growing research on CBM work demands development of a domain ontology in the CBM context to structure knowledge and data relevant to diagnosis and prognosis tasks, but with no actual ontology proposition [10].

An important concept related to this work is the concept of failure. A systematic technique for failure analysis called Failure Mode and Effects Analysis (FMEA) was first proposed by the NASA [11] to analyze system safety and reliability in a systematic way. Some works were proposed to describe FMEA knowledge using ontologies. [12] presents an UML based model to represent FMEA knowledge.

Supply chain ontologies are found in many works. TOVE Ontologies (acronym of Toronto Virtual Enterprise) [13] are a set of ontologies that aim to capture the infrastructure of an enterprise. Some of the ontologies reflect perspectives closer to a supply chain, namely resource, organization and activity-state-time ontology. The SCOR model (Supply Chain Operations Reference model) is used in the work of Fayez [14] to propose an ontology for supply chain simulation. According to the model, it is organized in the process plans: source, make, deliver, and return.

A supply chain ontology (SCO) was proposed by Ye [15] aiming to provide the semantic integration and interoperability across applications of supply chain members, acting as an “interlingua” for the application integration architecture. The SCOR model was used again as a basis for the knowledge modelling. It claims to be extensible, to support additional information and semantics of specific application domains.

A very interesting integration approach is presented by [16] 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.

2.2. Service-oriented architecture

Service-oriented computing represents a new paradigm in software engineering, where distributed applications are developed using the concept of services. Services are standardized self-describing interfaces, which encapsulate application functionality and can be combined to perform complex tasks, keeping the abstraction of component-based development [17]. The SOA approach addresses issues such as service addressing, announcement, self-description and service discovering, as well as registering in and looking up a central service repository (service registry).

The web services (WS) technology is currently the most employed solution to implement SOA across different layers of enterprise IT, as device and corporative layers [18].

2.3. Open interfaces for data exchange

The OSGi (Open Service Gateway Initiative) specification defines a service platform that relies on Java. An OSGi service is a simple Java interface, but the semantics of a service are not clearly specified. HAVi (Audio/Video Interoperability) offers plug-and-play as well as Quality-of-Service (QoS) capabilities and is targeted for the home automation domain. JINI (Java Intelligent Network Infrastructure) was developed by Sun Microsystems for spontaneous networking of services and resources based on the Java technology [17].

DPWS (Device Profile for Web Services) is a common web service middleware and profile for devices, which defines two fundamental elements:

1. devices that play an important part in the discovery and metadata exchange protocols
2. hosted services that provide functional behavior of the device and depend on their host for discovery

DPWS also specifies a set of infrastructure built-in services:

- Discovery services (WS-Discovery): used by a device connected to a network to advertise itself and to discover other devices
- Metadata exchange services (WS-MetadataExchange): provide dynamic access to devices hosted services and to their metadata, such as WSDL or XML Schema definitions
- Event publish/subscribe services (WS-Eventing): allow other devices to subscribe to asynchronous messages (events) produced by a given vendor-defined service

DPWS is built on top of the SOAP 1.2 standard, and relies on additional WS specifications, such as WS-Addressing and WS-Policy, to further constrain the SOAP messaging model. At the highest level, the messages correspond to vendor specific actions and events.

Common behavior of a DPWS endpoint consists of discovering relevant devices in the network, retrieving the device description and its set of hosted services, invoking operations on selected services to interact with the device, and ultimately subscribing to available event sources. DPWS thus provides a small and efficient framework for peer-to-peer device interaction [19].

3. Requirements analysis

3.1. Spare parts supply chain planning

The domain of SPSC shows some specific characteristics, which distinguish it from regular product supply chains and induce special requirements for the planning of SPSC.

First, the demand for spare parts and related maintenance services follows an intermittent and lumpy pattern [20]. These varying changes of zero-demand periods and periods with comparatively high demand pose a particular challenge for demand forecasting activities as well as the subsequent planning activities of production, inventory, transportation and maintenance planning [21]. Moreover, the structures of SPSC mostly comprise a diverging network resulting in multi-echelon inventory situations, i.e. the inventory is being kept on multiple stages of the network. Furthermore, in case a machinery breakdown happens at the final customer's site, replacements for the broken part(s) are requested and the right spare parts – and if necessary qualified service personnel and equipment – need to be delivered to the right place in the right quantity at the right time. The presence of service level agreements requires that the delivery and repair is performed fast enough in order to guarantee the service levels. This could result in high inventory levels for spare parts along the SPSC enabling the effective fulfillment of customer demand, but also causing high distribution costs.

In order to deal with these intertwined issues of the complex problem structure and to increase the efficiency of a SPSC, a better knowledge about the degradation status of the machinery to be maintained would be desirable. This information could be automatically applied for the planning of the SPSC activities, e.g., by incorporating it in advanced failure and demand forecasting as well as machine control – resulting in a more efficient SPSC planning that could reduce total costs throughout the SPSC as well as ensuring the agreed-upon service level.

3.2. IT systems being applied

For the planning of a SPSC, a multitude of different IT systems usually is applied. Fig. 1 shows a typical setup of a SPSC including actors involved, related planning domains and applied IT systems. Certain systems that are used to plan a general product supply chain, e.g., advanced planning systems (APS), are also applied to the planning of the after-sales part – the SPSC. Furthermore, specific systems are introduced that are dedicated to the exclusive planning of SPSC activities, e.g., computerized maintenance management systems (CMMS).

The primary task of an APS is to support the decision making for supply chain management by planning a large range of activities across the supply chain [22]. An APS is composed of specialized and intertwined software modules that cover important planning domains of the supply chain, e.g., production, transportation or inventory management [23]. The modules provide related planning methods and algorithms and take limited availability of resources into consideration.

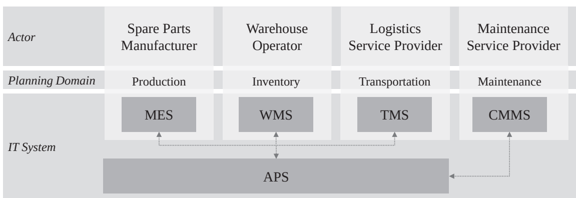

Fig. 1. SPSC actors, planning domains and IT systems.

Moreover, APS can interact with further specialized IT systems being applied in a SPSC, e.g., in order to obtain better demand forecasts that are the basis for planning or leveraging real-time information about the execution of plans provided by a manufacturing execution systems (MES), transportation management systems (TMS) or warehouse management systems (WMS).

The basic idea of CMMS is to support maintenance decision making by monitoring and controlling assets of a company [24]. By acquiring, storing and analyzing information about the individual machines to be maintained, different activities are facilitated, e.g., the planning of maintenance service activities or inventory levels of spare parts [25]. Based on the historical information including costs and results of performed maintenance activities, CMMS can help to plan future maintenance activities by evaluating old maintenance plans and devising new maintenance policies. Following the idea of condition-based maintenance, the gathered condition monitoring information could be used to generate forecasts for potential future machine failures. Moreover, it would be favorable to share condition monitoring information, failure forecasts and maintenance schedules with APS systems in order to enable a better demand forecast and subsequent planning of the SPSC.

3.3. Intelligent maintenance systems

By combining computational software, embedded sensors and communication networks, an IMS generates and provides condition monitoring information about a machine [26]. Besides the pure sensor data provision, an IMS evaluates the degree of degradation of a machine and its parts, i.e. the working state of the machine parts as well as its state in the overall life-cycle. Within the set of evaluation approaches being proposed in literature, one of the most important to be considered is the Watchdog Agent [27]. It comprises a set of algorithms in order to interpret sensor data, predict failures and degradation and evaluate the working state of a machine. To sum up, the application of IMS enables the shift from traditional reactive maintenance activities, which repair a machine after a breakdown has occurred, to proactive maintenance activities, in which machines are maintained and parts being replaced before an actual breakdown takes place.

3.4. Identification of concepts for information exchange

In order to facilitate the benefits to be achieved by a proper and automated integration, planning-related information that is to be exchanged between both domains was considered as well as the identification of the systems being involved, which enable the information exchange. The IT systems being involved in SPSC planning, depicted in Fig. 1, show two key systems to incorporate IMS into SPSC planning: CMMS and APS.

Embedded IMS provides condition monitoring information about the individual status of the machine. This also includes information about the degradation of specific parts of the machine. The information comprises e.g., identifier of the machine, identifier of a specific degraded machine part, breakdown probability distribution, estimated breakdown date, and is to be transmitted to the CMMS managing the machine.

The CMMS – managing multiple machines of a plant or company – aggregates and enriches the condition monitoring information of individual machines in order to facilitate enhanced forecasts for machine failures and related demands for spare parts and maintenance services. Therefore, this aggregated and enriched condition monitoring information is to be transmitted to the APS that manages and plans the SPSC being responsible for the provision of spare parts and maintenance services. The exchanged information includes in addition to the information provided by the individual machines, e.g., geographic locations of the machines, (alternative) spare parts to be used for repair, related parts that need to be replaced as well, required service personnel capability and equipment. Furthermore, the decision of when to request maintenance service for a machine is made by the CMMS and a specific request for maintenance including the preferred date for executing the maintenance service is sent to the APS.

The aggregated and enriched condition monitoring information as well as requests for maintenance could be used by the APS in order to achieve better forecasts for spare parts, maintenance demands and following enabling an enhanced planning of the SPSC that anticipates the future demand while planning e.g., machine and (service) personnel capacities, inventory and safety stock levels or transports. After having planned and scheduled maintenance services for specific requests from a CMMS, the confirmation of the planned service is to be sent to the CMMS, including e.g., scheduled dates of maintenance services. This enables the CMMS to take further measures and to alter the mode of operation of the machine to be maintained. For instance, in case the confirmed date of maintenance services is later than the estimated breakdown date, the machine could be slowed down in order to last longer. Fig. 2 shows the key information being exchanged between the systems involved.

4. Solution approach

4.1. Development of integration ontology

A combination of three complementary approaches has been applied for developing the design of the ontology concepts that are related to the information exchange between IMS and SPSC systems. In total, the inspirational, synthetic and collaborative design approaches have been applied [28]. The inspirational approach has been chosen, because a significant part of the work is developed through individual work and research from the authors.

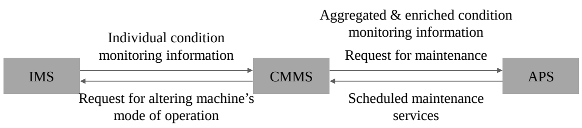

Fig. 2. Key information exchanged and related systems.

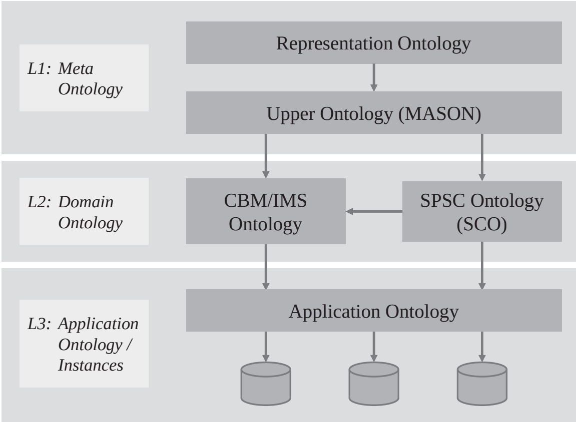

Fig. 3. Multi-layer ontology.

Following the synthetic approach, the ontology has been built on previous works and base ontologies. Since this work is embedded in an international research project, the collaborative approach has been applied resulting in contributions and evaluation by partners and experts from different areas.

Based on the previously presented approach of integrating IMS and SPSC domains by means of an integration ontology [4], we extended the multi-layered ontology proposed by Jian and Jianyuan [16] and present the resulting multi-layer integration ontology in Fig. 3. 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 application case specific details are defined. The first layer, meta ontology, includes the representation and upper ontology. Representation describes the characteristics of the ontology: its attributes and relationships. The upper ontology represents common sense knowledge, not related to a specific domain. The domain ontology layer describes professional terms for spare parts supply chains and CBM/IMS in particular. Semantically speaking, its purpose is to specify with more detail what is conceptualized by the upper ontology, based on the considered domains. In this case, we consider IMS, CBM and spare parts supply chains as the domains to be modelled.

Finally, the application ontology / instances layer contains knowledge that is related to specific business cases. This includes additional concepts as well as specific instances of concepts. 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 conceptually model every concept of all kinds of business.

The SPSC ontology is based on the Supply Chain Ontology of Ye [15] and was extended in order to reflect necessary parts of the SPSC domain and enable the integration with the CBM/IMS domain. For example, execution and planning services have been detailed in order to specify maintenance activities being supported by deployed IT systems resources like CMMS and APS. Data to be exchanged between different systems and inherits the concept Information Object that is shared between processes. Fig. 4 presents a snapshot of this extension, showing also the IMS concept and some concepts integrating the SPSC with CBM/IMS domain.

4.2. Development of service-oriented architecture

The IT support for the data exchange was built using a DPWS-based architecture and modeled based on the integration ontology.

Three types of DPWS devices are defined: IMS device, CMMS device and APS device. The CMMS device hosts the "CBM board" service, which enables IMS devices to report the health condition information and maintenance demand. APS devices host the maintenance request service, used by CMMS to request spare parts and/or specialized maintenance services.

When a device requests a service, it also subscribes to an event that acts as a request callback. For instance, when the CMMS requests a set of spare parts, after planning the SPSC, the APS will return the estimated delivery date.

For DPWS devices and services implementation, the Java Multi Edition DPWS Stack (JMEDS) by WS4D is used [17]. IMS functionalities are provided by an IMS Simulator, which is built using the Matlab Watchdog Agent toolbox [27] with an Java interface to integrate with JMEDS.

5. Validation

For validation purposes, a study case was developed using a valve manufacturing company and defining the specific concepts related to this company. 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. The real valves were also represented by instances of valve concepts, as well as the composition of the supply chain. This approach demonstrates how real cases can be modelled using detailing of upper layer concepts in the application/instantiation layer.

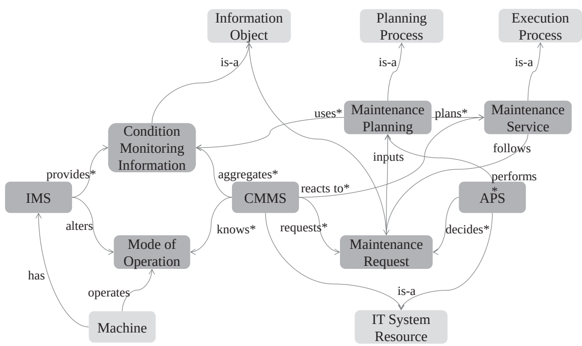

Fig. 4. Main integration concepts and relations.

IMS simulators use data from previous works [29] to emulate IMS behavior and generate information to the CMMS device. Functionality implemented by the CMMS device is to group information from all IMS devices, package it in the specified format and send it to the APS device. This scenario allows testing the data exchange modeled by the ontology as the services implemented by the DPWS.

6. Conclusion

The key issue for incorporating condition monitoring information in the forecasting and planning of a SPSC is the integration of IMS and SPSC systems – enabling the required exchange of information. The proper integration is based on a common terminology and integrating architecture. The proposed ontology concepts facilitate the semantic integration and utilization of exchanged information. Furthermore, they are used to derive service-oriented integration architecture for the identified IT systems being involved. The usage of DPWS as support for the SOA implementation is a successful strategy, since DPWS provides the register/discovery functionality allowing a quick SOA network configuration. A case of a manufacturer producing automation solutions for the oil industry was used to test the validity of the proposals. Future research will target advancements of the proposed integration by validating the maturity in other cases and industries.

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