Knowledge Sharing and Reuse in Potential Failure Mode and Effects Analysis in the Manufacturing and Assembly Processes (PFMEA) Domain

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Abstract. The Potential Failure Modes and Effects Analysis in Manufacturing and Assembly Processes (PFMEA) represents an important preventive method for quality assurance, in which several specialists are involved in the investigation of all the causes and effects related to all possible failure mode of a manufacturing process, still in the initial phases of its development. Thus, the decisions based on the severity levels of effects and on the probabilities of occurrence and detection of the failure modes can be planned and prioritized. The result of this activity consists of a valuable source of knowledge about the manufacturing processes. However, this knowledge is hardly reusable in intelligent retrieval systems, because in general all related information is acquired in the form of natural language and it is not semantically organized, and therefore its meaning depends on the understanding of the specialists involved in the production chain. In this context, this paper describes the development and implementation of a formal ontology based on description logic (DL) for the knowledge representation in the domain of PFMEA, which fundamentally intends to allow the computational inference and ontology-based knowledge retrieval as support to the activities of organizational knowledge in manufacturing environments with distributed resources.

Keywords. PFMEA, Knowledge Representation, Ontology, Description Logic

1 Introduction

The Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes (PFMEA) is an analytical method of quality engineering for the analysis of a manufacturing process, still in the initial phases of its development, in order to identify all of the potential failure modes, their causes and effects on process

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performance. And, consequently, starting with the results of this systematic analysis, the engineers can review their processes in order to propose actions that aim at eliminating or reducing significantly the probability of occurrence of these failure modes, or to increase the detection probability of the failure mode associated with a certain cause [16].

Due to its relevance, the theme of PFMEA has been discussed significantly in the literature and, especially, a common characteristic stands out, which is: when the PFMEA method is carried out in an appropriate way, it results in a significant amount of pieces of information and knowledge about the processes of an organization, and therefore it is a valuable source that can provide technical support to the anticipated detection of weak points in a process design, cost reduction along the product life cycle, and lower levels of modifications during the production phase [17, 5].

However, this valuable knowledge obtained at a high cost is hardly shareable and reusable in the context of intelligent knowledge retrieval systems, since the functions and failure modes concepts, among others, are not semantically organized. So, its meaning will depend on the human interpretation. Also, due to the great amount of information and current knowledge resulting from the FMEA analyses already accomplished as well as the fragmentation and distribution that usually happens along the production chain, the reutilization task becomes imprecise and unproductive [17, 5].

On the basis of these issues, this paper describes the development and implementation of a formal ontology for knowledge representation in the PFMEA domain, with an alternative to the problem of semantic barrier. The proposed ontology was coded through the OWL DL (Web Ontology Language - Description Logic) language pattern [20], as a means to enable the knowledge sharing and reuse in an agent-based mediated knowledge management context.

2 Ontology as a Knowledge Representation

In the last few years, researches on the use of ontology as a way to represent knowledge has been essential in many applications, which include multi-agent systems, knowledge management systems, intelligent integration of information, and semantic-based access to the Internet [1]. In particular, Dittmann *et al.* [5] and Lee [10] suggest that the use of ontologies can be an innovative alternative to represent the knowledge resulting from the application of the Failure Modes and Effects Analysis method.

However, in the literature there is no universally agreed formal definition of ontology. Thus, in this paper, the adopted definition is the one proposed by Zúñiga [21]: “an ontology is an axiomatic theory made explicit by means of a specific formal language” and “is designed for at least one specific and practical application” and “consequently, it depicts the structure of a specific domain of objects, and it accounts for the intended meaning of a formal vocabulary or protocols that are employed by the agents of the domain under investigation.”

2.1 Description Logic as a Formal Ontology Language

Description Logic (DL) is the most recent family of formal languages of knowledge representation based on first-order logic, and consists of basic descriptions of the application domain, *i.e.*: atomic concepts for the classes or group of individuals with similar characteristics; atomic roles for properties of these concepts or binary relations between individuals, and from them, other complex descriptions that can be constructed as axioms using a set of logical operators called concepts constructors [3].

A knowledge base that refers to an application domain, formalized through description logic, comprises two fundamental components [3, 8, 18]: (a) TBox, a terminological component, which represents the intentional knowledge or the knowledge about the characteristics of the concepts, comprising a group of terminological axioms that define these concepts from other primitive concepts and roles; (b) ABox, an assertional component, which represents the extensional knowledge or the specific knowledge about the individuals (instances) and their relationships within the same abstraction level, represented by an additional group of assertional axioms, which reflect the instantiation of the terminological component.

In spite of the potential of the formal languages based on description logic in the realm of knowledge representation, their real applicability takes place through the computer systems that implement them, as well as the capacity of those systems to process the represented knowledge in an explicit way with the objective to infer implicit knowledge through a specific inference service [13].

Many different computer systems with inference services are presented in the literature, among which is the RacerPro Server System [13], which is used in this work, and it provides reasoning service based on tableaux algorithms [4] for the language of descriptions logic $ALCQHI_{R+}$ [8], as well as making available a semantically well-defined ontology-based query language (nRQL, new RacerPro Query Language) and the nRQL query processing engine that can be accessed by the default TCP communication port [13].

3 Development of the PFMEA-DL Ontology

The development of ontology consists of a group of activities of conceptual modeling and, therefore, it should be based on consistent methods and methodologies on a scientific point of view.

Thus, in the context of this work it was adopted the so-called Methontology methodology proposed by Fernándes-Lopés *et al*. [6], based on the IEEE standard for software development. In this paper, the activities of the development process will be highlighted: conceptualization and implementation.

3.1 Conceptualization of the PFMEA DL Ontology

The PFMEA-DL Ontology proposed in this work was developed in its conceptual phase in consonance with the concepts and terms established in the SAE J1739 standard [15] and in the AIAG reference [2], thoroughly used in the area of quality engineering. Thus, the knowledge domain was modeled considering the description of concepts and their relationships starting with seven main concepts elements: Product, Process, Function, Failure, Actions, FMEA Description and Images.

In this scenario, the Product Concepts represent the domain of the product model, particularly its logical structure, and it corresponds to the classes and subclasses of products. The Process Concepts represents the logical and temporal structure of the processes, their respective operations and pieces of equipment, for a given industrial plant. The Function Concepts comprises a model of functions associated with each process or operation.

In the Failure Concepts the fundamental concepts and relationships of the PFMEA method are represented, which include: potential failure mode, effect of failure, causes of failure. In an innovative way it links the concept of potential failure mode with the concepts of primary and secondary identifiers, as well as the allocation of the failure with regard to a model of features as proposed by Shah and Mäntilä [14]. This is done in order to reduce the possible ambiguity between the instances of the concept Potential Failure Mode and to increase the expressiveness of the semantic representation of the knowledge and the capacity of the inference service and knowledge retrieval tasks. Figure 1 illustrates the model of concepts and roles (binary relationships) among instances for the Failure Concepts.

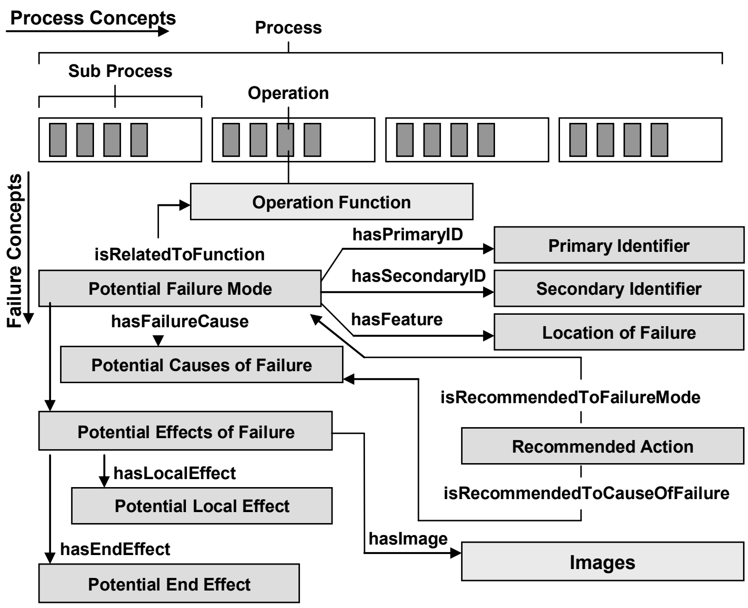

Figure 1. Model of concepts and roles of the Failure Concepts element

The concept of "primary identifier" represents the generic aspects related to the failure manifestation and failure inducing agent, involving: the main characteristic of the failure mode, or still the characteristic of the environment under which the failure mode occurred, or the kind of solicitation. The "secondary identifier" represents the aspects related to: types of involved materials, characteristics of failure or presence of other factors or specific means. For example: Failure Mode: Direct chemical attack; Primary Identifier: Corrosion; Secondary Identifier: surface exposed to corrosive media [19].

In the Action Concepts, the concepts and current relationships resulting from the risk analysis of the PFMEA method are represented, such as: current process control for prevention and detection, a rating criteria (severity scale, occurrence scale and detection scale), risk priority number, recommended actions, actions taken and responsibilities. The FMEA Description represents the other concepts regarding the core teams and responsibilities.

Finally, the ontology includes the Image Concepts, whose objective is to represent the concepts and relationships, such as: material description, metallographic preparation, and material processing history, besides the concepts related to the image type and image source, allowing the semantic-based image indexing related to a failure effect.

3.2 Implementation of the PFMEA DL Ontology

The PFMEA-DL ontology was implemented through the standard language for ontologies OWL DL (Web Ontology Language - Description Logic), developed by W3 Consortium [20], which combines a great power of expressiveness with the possibility of the inference service common to the description logic [9], using the Protégé-OWL Ontology Editor [12].

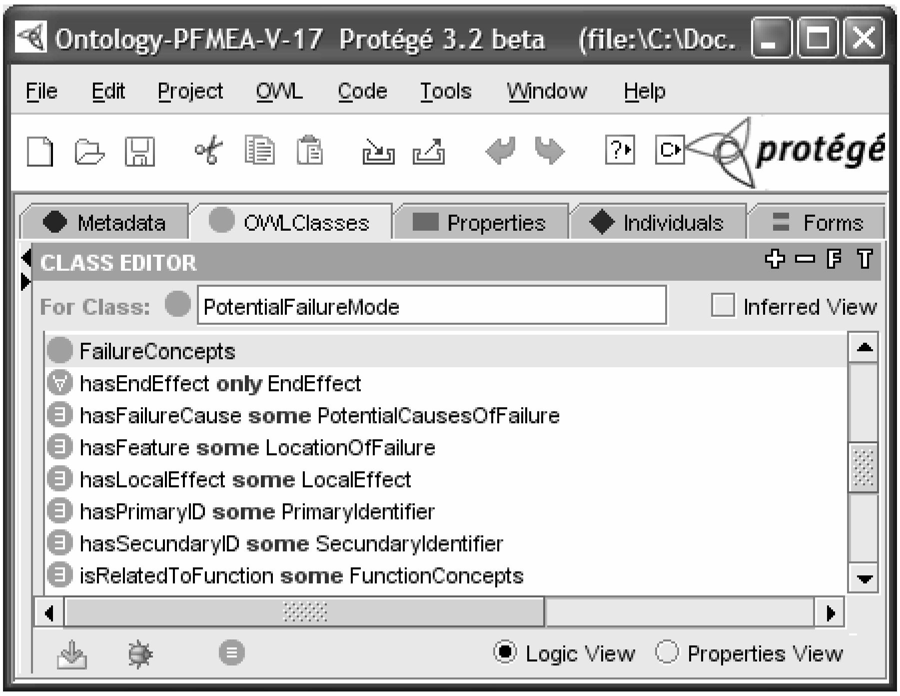

Figure 2. Protégé OWL Classes Tab snapshot

In this context, figure 2 presents the logical structure of classes and subclasses modeled in the Protégé OWL Editor, demonstrating the application of the property restriction to the OWL Subclass PotentialFailureMode.

It is important to observe that the application of the existential quantifier restrictions ∃ in Equation 1, is analogous to the existential quantifier of Predicate Logic and consist of describing an anonymous "unnamed" class that restricts a group of individuals (instances) of the subclass "PotentialFailureMode" connected to individuals of the "PotentialCausesOfFailure" subclass, through the "hasFailureCause" object property, which will be determined automatically by the inference service of the reasoning engine.

$$\exists\ \text{hasFailureCause some PotentialCausesOfFailure} \quad (1)$$

Along the process of development of the ontology, with the purpose of maintaining the methodological coherence, an ontology evaluation approach was adopted starting with the dimensions proposed by Gangemi *et al*. [7], which are as follows: structural, functional, and usability-profiling. In this work the functional dimension stands out.

The functional evaluation involved, initially, instancing the proposed ontology starting with a knowledge body of reference already validated, which resulted from the application of the PFMEA method by manufacturing processes specialists of a company producing roller bearings in the realm of a SixSigma project [11]. By applying this example, it was possible to evaluate the accuracy of the PFMEA-DL Ontology, confronting the answers from the inference service and the knowledge retrieval tasks accomplished with the concepts, relationships and instances represented in the ontology with the cognitive model presented in the literature.

Figure 3 shows an example of a complex query from the ABox perspective.

```
RacerPro Log
? (RETRIEVE
    (?POTENTIAL_CAUSES_OF_FAILURE ?POTENTIAL_END_EFFECT_OF_FAILURE)
    (AND (?POTENTIAL_CAUSES_OF_FAILURE
         |http://www.owl-ontologies.com/Ontology1144700912.owl#PotentialCausesOfFailure|)
        (?POTENTIAL_END_EFFECT_OF_FAILURE
         |http://www.owl-ontologies.com/Ontology1144700912.owl#EndEffect|)
        (?POTENTIAL_CAUSES_OF_FAILURE
         ?POTENTIAL_END_EFFECT_OF_FAILURE
         |http://www.owl-ontologies.com/Ontology1144700912.owl#isRelatedToEndEffect|)
        (?POTENTIAL_CAUSES_OF_FAILURE
         |http://www.owl-ontologies.com/Ontology1144700912.owl#Oil_remainder_on_cage|
         |http://www.owl-ontologies.com/Ontology1144700912.owl#isACauseOfFailureMode|)
        (?POTENTIAL_END_EFFECT_OF_FAILURE
         |http://www.owl-ontologies.com/Ontology1144700912.owl#Oil_remainder_on_cage|
         |http://www.owl-ontologies.com/Ontology1144700912.owl#isAEndEffectOfFailureMode|)))

> (((?POTENTIAL_CAUSES_OF_FAILURE
     |http://www.owl-ontologies.com/Ontology1144700912.owl#Temperature_to_low_in_washing_bath|)
    (?POTENTIAL_END_EFFECT_OF_FAILURE
     |http://www.owl-ontologies.com/Ontology1144700912.owl#Stained_phosphating|))
   ((?POTENTIAL_CAUSES_OF_FAILURE
     |http://www.owl-ontologies.com/Ontology1144700912.owl#Spooling_mouthpiece|)
    (?POTENTIAL_END_EFFECT_OF_FAILURE
     |http://www.owl-ontologies.com/Ontology1144700912.owl#Stained_phosphating|))
```

Figure 3. Complex ABox query and their results - RacerPro Log snapshot

The objective of this complex query (figure 3) is to recover all the Potential End Effects and the Potential Causes of Failure for a given Potential Failure Mode, which is an instance of the concept Potential Failure Mode, in this case “Oil remainder on cage”. It is important to observe that the query combines concepts atoms (#PotentialCausesOfFailure) and role atoms (#isRelatedToEndEffect) through the query constructor “and”.

The end effects is the impact of a possible failure mode on the highest process level and is evaluated by the analysis of all the intermediate levels, and it may result from multiple failure modes. Thus, in figure 3, the instance “Temperature too low in washing bath” is a potential cause of the failure mode “Oil remainder on cage” and its respective end effect is the instance “Stained phosphating”.

However, nRQL also provides complex TBox queries to search for certain patterns of sub/superclass relationships in taxonomy (OWL Document) [8].

4 Summary

This paper presented the development of a formal ontology based on description logic (DL) for the knowledge representation in the PFMEA domain. The proposed ontology was developed from the conceptual point of view, in consonance with the concepts and terms widely recognized in the quality context.

The proposed ontology was implemented through the OWL DL (Web Ontology Language - Description Logic) and the RacerPro Server was used as core engine for reasoning services and nRQL query processing.

The functional evaluation showed the semantic consistency and the applicability of the proposed ontology to support knowledge sharing and reuse in the PFMEA domain, as well as being promising as support to the activities of organizational knowledge in manufacturing environments with distributed resources.

Finally, the proposed ontology was developed as a means to work as a terminological component TBox for other specific knowledge base for applications toward complex manufacturing processes, *e.g.* in thermoplastic injection moulding, in future ontology-based knowledge retrieval systems applications, and for agent-based mediated knowledge management.

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