SHARING AND REUTILIZING CURRENT KNOWLEDGE ABOUT THE APPLICATION OF THE POTENTIAL FAILURE MODES AND EFFECTS ANALYSIS IN MANUFACTURING PROCESSES (PFMEA)

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Abstract. *The Potential Failure Modes and Effects Analysis in Manufacturing and Assembly Processes (PFMEA) represents nowadays an important preventive method for quality assurance, in which several specialists are involved in the investigation and evaluation 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, it can be planned and prioritized the decisions based on the severity levels and probabilities of occurrences and detection of the failure modes, aiming at improving the quality of the products produced by these processes. The result of this activity consists of a valuable source of knowledge about the manufacturing processes in the company. However, the sharing and the reutilization of this knowledge is a challenge, because in general all related information is acquired in the form of natural language, and therefore it is not represented in the form of explicit knowledge. In this context, the objective of this paper is to present the development and implementation of a formal ontology based on description logic (DL) for the representation of knowledge in the domain of PFMEA, which fundamentally intends to allow the inference and knowledge retrieval computationally as support to the activities of organizational knowledge in manufacturing environments with distributed resources. The paper analyzes and discusses the results of the implementation of the PFMEA-DL ontology related to a machining process of a mechanical part.*

Keywords: *FMEA, PFMEA, Ontology, Description Logic.*

1. INTRODUCTION

Nowadays, the social and economical environment is characterized by the appearance of new forms of industrial organizations, caused by complex factors such as market globalization, product life cycle reduction, high demand variability, need of high flexibility and reactivity, and fast development of the technologies of information and communication[1].

In this context, the new forms of organizational structures have been recognized by the scientific community and other professionals of this area, which include: extended enterprise, virtual enterprise, virtual organization, supply chain management and enterprise clusters[1,2].

The key problem in these environments consists of integrating the distributed resources that contribute to production, considering that these new organizational structures are geographically distributed, composed by different commercial partners, each of them endowed with specialization and resources for a specific function in the product life cycle[2].

In this scenario, with a view of quality, the management and improvement systems should cover not only the internal functions of organization, but to expand to external functions related to every chain involved[3]. In this context, Failure Modes and Effects Analysis (FMEA) is a quality engineering method, thoroughly used in the improvement processes, and the accumulated information on manufacturing constitutes a valuable knowledge that should be shared.

Approaches found in the literature are proposed with the use of tools for the quality information management, whose purpose are to capture information about quality starting with internal and external sources to the organization to facilitate the communication environment, aiming at sharing information and knowledge related to the quality among companies, customers and suppliers through the Intranet/Internet[3].

Considering the scenario above, this paper presents the development of a formal ontology based on description logic (DL) for the representation of knowledge in the domain of the Potential Failure Modes and Effects Analysis in Manufacturing and Assembly Processes (PFMEA), which aims at sharing and reutilizing current knowledge about the application of this method in support to the activities of management of the organizational knowledge regarding processes in manufacturing environments with distributed resources.

The PFMEA-DL (PFMEA with Description Logic) ontology proposed is based on the concepts and terms of the SAE J1739 standard[4] and on the AIAG reference[5]. The proposed ontology includes pertinent concepts to the images that can be associated with a process failure, because images are, in general, fundamental elements of the process of failure analysis. And, additionally, it includes the concepts of primary and secondary identifiers associated with the failure mode concept and the location failure concept associated with the manufacturing features model, aiming at increasing the expressiveness of the semantic representation of knowledge.

Finally, the paper discusses the results of the implementation of the PFMEA-DL ontology through the standard ontology language OWL-DL (Web Ontology Language - Description Logic)[6] using as graphic editor the Protégé-OWL knowledge modeling platform[7] and as description logic (DL) reasoning engine the RacerPro system[8]. That is done through the instancing of the ontology with a body of reference knowledge, obtained from the application of the PFMEA method by specialists in manufacturing processes of a company that produces roller bearings[29].

2. KNOWLEDGE REPRESENTATION RELATED TO THE FMEA METHOD

Potential Failure Mode and Effects Analysis (PFMEA) is an important analytical method of quality engineering, whose purpose is, still in the initial design phases, to analyze all of the potential failure modes of a system, product or process, the potential cause of the failure associated to each one of those failure modes, as well as their effects. And, consequently, starting with the results of this systematic analysis, the designers can review their designs 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[9].

Due to its relevance, the theme of FMEA has been discussed significantly in the literature and, especially, a common characteristic stands out, that is, the FMEA method, when carried out in an appropriate way, it results in a deep set of pieces of information about the systems, products and processes of an organization, and therefore it is a valuable source of information and knowledge that can provide technical support to the anticipated detection of weak points in a design, reduction of the costs along the product life cycle, and lower levels of modifications during the production phase(10,11).

However, this valuable knowledge obtained at a high cost is difficult to be shared and reused, therefore the functions and failure modes, among other, are not represented in an explicit way. So, its semantics will depend on the human interpretation and, besides, the great amount of information and current knowledge resulting from the FMEA analyses already accomplished turns the reutilization task imprecise and unproductive.

In this scenario, Dittmann *et al*.(11) and Lee(12) proposed the use of ontologies as an innovative alternative to model and to treat the knowledge resulting from the Failure Modes and Effects Analysis in Design (Design-FMEA) as a means to help solve the identified problems.

2.1. Knowledge Sharing, Ontology, Ontology Languages and Description Logic

In the last few years, researches on the use of ontologies as a way to represent knowledge, which allows inference service on the represented knowledge, as well as its sharing between human or computer agents, 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(13,14).

However, in the literature of the areas not related to philosophy, especially information systems, computer science, artificial intelligence, and cognitive sciences, there is no universally accepted definition of the term ontology, although the most known definition has been presented by Gruber(15).

In this paper the adopted definition is the one proposed by Zúñiga(16), in which 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."

Description Logic (DL) corresponds to the most recent family of formal languages of knowledge representation based on first-order logic, and they appeared as an alternative to the knowledge representation based on *ad hoc* data structures, such as semantic networks and frames(17).

In this perspective, different formal languages of the family of description logic are presented and discussed in the literature(17,18,19). These languages present differences between them because of the set of logic constructors that each language can support.

A knowledge base, referring to an application domain, formalized through description logic comprises two fundamental components: (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(17); (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, modeled 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(18,19,20).

Nowadays there are several computer systems with inference service based on tableaux algorithms(20). For description logic, in particular, the RacerPro Server System can be mentioned (*Renamed ABox and Concept Expression Reasoner Professional*), which is a knowledge representation system that implements the tableaux algorithm for the language of descriptions logic $ALCQHI_{R+}$, also known as *SHIQ*(8,18), and it offers different inference services, such as: concept consistency checking and ABox consistency checking with regard to a given TBox concerning the possible error or contradiction modeling in the definition of the concepts and instances, 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 [8].

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. In this sense, Corcho *et al.*[13] present an extensive review on the main methodologies found in the literature about the construction of ontologies.

Thus, in the context of this work it was adopted the so-called Methontology methodology proposed by Fernándes-Lopés *et al.*[22], based on the IEEE standard for software development, which comprises a development process that establishes a group of specific activities for the construction of the ontology, a life cycle that defines the sequence of the development activities, and the activities of the process of design management. In this paper, the activities of the development process will be highlighted: conceptualization, formalization, and implementation.

3.1. Conceptualization and formalization of 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[3] and in the AIAG reference[4], thoroughly used in the area of quality engineering. Thus, the knowledge domain was modeled considering the description of concepts and their relationships (roles) starting with seven main axes: Product Concepts, Process Concepts, Function Concepts, Failure Concepts, Action Concepts, FMEA Description and Images Concepts, as it is shown in figure 1.

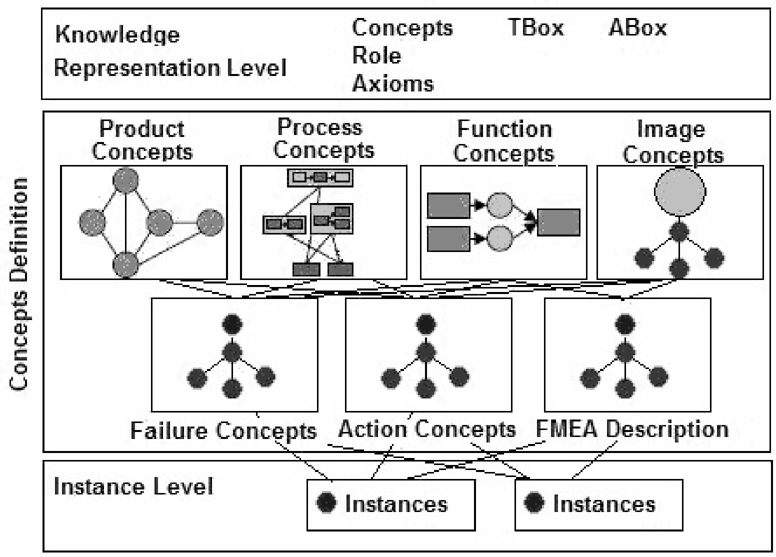


Figure 1. Concepts represented in the PFMEA DL

In this scenario, the Product Concepts represents the domain of the product model, particularly its logical structure, and it corresponds to the classes and subclasses of products as described in Madsen and Hjulstad[23]. The Process Concepts represents the logical and temporal structure of the processes, their respective operations and pieces of equipment, for a given industrial plant and the respective teams. The Function Concepts comprises a model of functions associated with each process or operation.

In the Action Concepts (figure 1), 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 PFMEA Description Concepts represents the other concepts regarding the core teams and responsibilities[3, 4].

In the Failure Concepts (figure 1) the fundamental concepts and roles (binary relationships) of the PFMEA method are represented, which include: potential failure mode, potential effect of failure, potential causes of failure, and 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[24], whose main objective is to increase the expressiveness of the semantic representation of the knowledge and the capacity of the inference service and knowledge retrieval tasks. Figure 2 illustrates the model of concepts and binary relationships (roles) among instances for the Failure Concepts element.

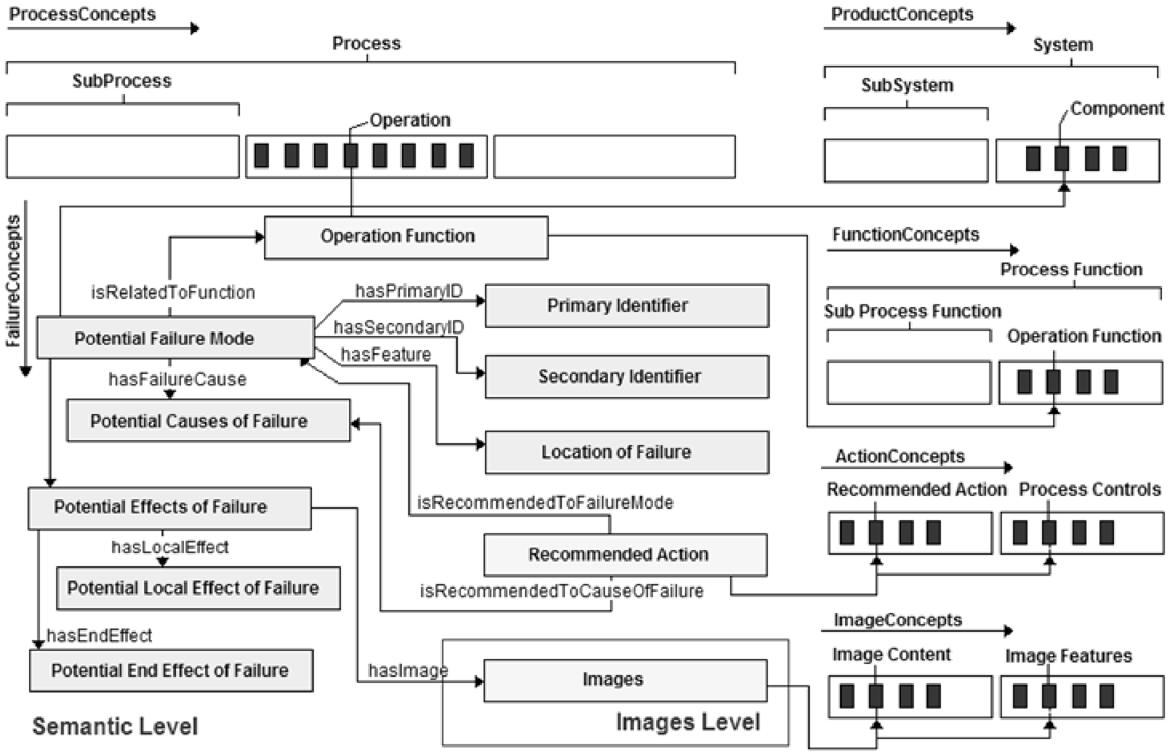


Figure 2. Model of concepts and roles of the Failure Concepts element

In this sense, the features are defined as generic shapes or characteristics of a part, to which it is possible to associate certain attributes, information and knowledge that will be useful during product manufacture.

The concept of primary identifier (figure 2) represents the generic aspects related to the form of failure manifestation, involving: the nature or type of request, the main characteristic of the failure mode, or still the characteristic of the environment under which the failure mode occurred[25,26]. And the secondary identifier represents the aspects related to the inductor agents of the failure mode, such as: types of involved materials, or the presence of other factors or specific means.

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.

3.2. Implementation of the PFMEA DL Ontology

The PFMEA-DL ontology was implemented through the standard language for ontologies called OWL DL (Web Ontology Language - Description Logic), developed by World Consortium[6], which combines a great power of expressiveness with the possibility of the inference service common to the description logic[27], using the Protégé-OWL knowledge modeling platform[7].

As description logic (DL) reasoning engine responsible for the inference service and knowledge retrieval, the RacerPro Server System[8] that can be accessed by the default TCP communication port was chosen. RacerPorter[8] was adopted as graphical user interface, which allows the manipulation of knowledge bases in the OWL DL language, to visualize the TBox and ABox components of an ontology, as well as to send queries in the nRQL (new RacerPro Query Language) search language, as it is shown in figure 3.

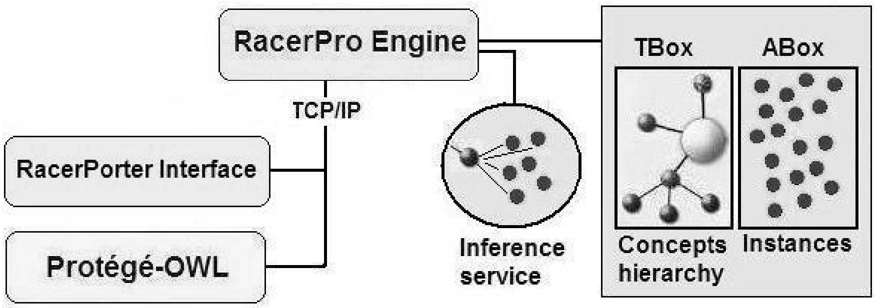


Figure 3. Software resources used in the implementation

In this context, figure 4 presents the logical structure of classes and subclasses modeled in Protégé OWL[7], in agreement with the established concepts and, especially it demonstrates the application of the existential quantifier restrictions to the description of the OWL PotentialFailureMode subclass, that is an powerful way of describing and defining classes[7].

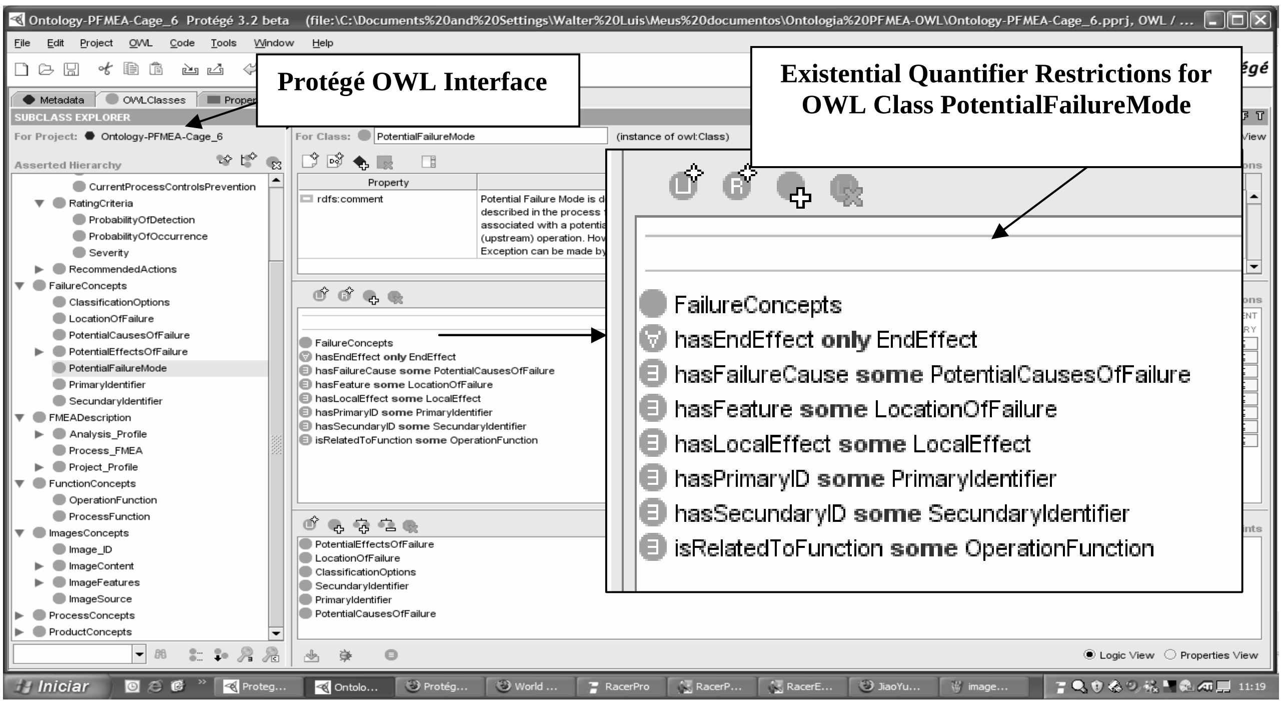


Figure 4. Representation of PFMEA-DL in Protégé OWL

∃ hasFailureCause some PotentialCausesOfFailure (1)

It is important to observe that the application of the existential quantifier restrictions (∃) represented in Equation 1, is analogous to the existential quantifier of Predicate Logics, which can be read as *at least one* (or *some*). The role (binary relationship) given by the object property “hasFailureCause” and the subclass “PotentialCauseOfFailure” consist of describing an anonymous “unnamed” class that restricts a group of individuals (instances) of the subclass “PotentialFailureMode” connected to individuals of the “PotentialCauseOfFailure” subclass, through the “hasFailureCause” OWL Object Property, which will be determined automatically by the inference service of the reasoning engine.

∃ isRelatedToFunction some OperationFunction (2)

Similarly, in the OWL expression (Equation 2), the OWL Object Property “isRelatedToFunction” was also modeled as an inverse property of “hasFailureMode”, and thus the reasoner, based on this knowledge, can start to infer that an individual of the “OperationFunction” subclass is connected to other individual of the “PotentialFailureMode” subclass by the “hasFailureMode” object property.

3.3. Evaluation of the PFMEA DL Ontology

Along the process of development of the PFMEA-DL ontology, with the purpose of maintaining the methodological coherence, an ontology evaluation approach was adopted starting with the dimensions proposed by Gangemi *et al*.[28], concerning the evaluation of the dimensions: structural, functional, and usability-profiling. In this work the evaluation accomplished for functional dimension stands out.

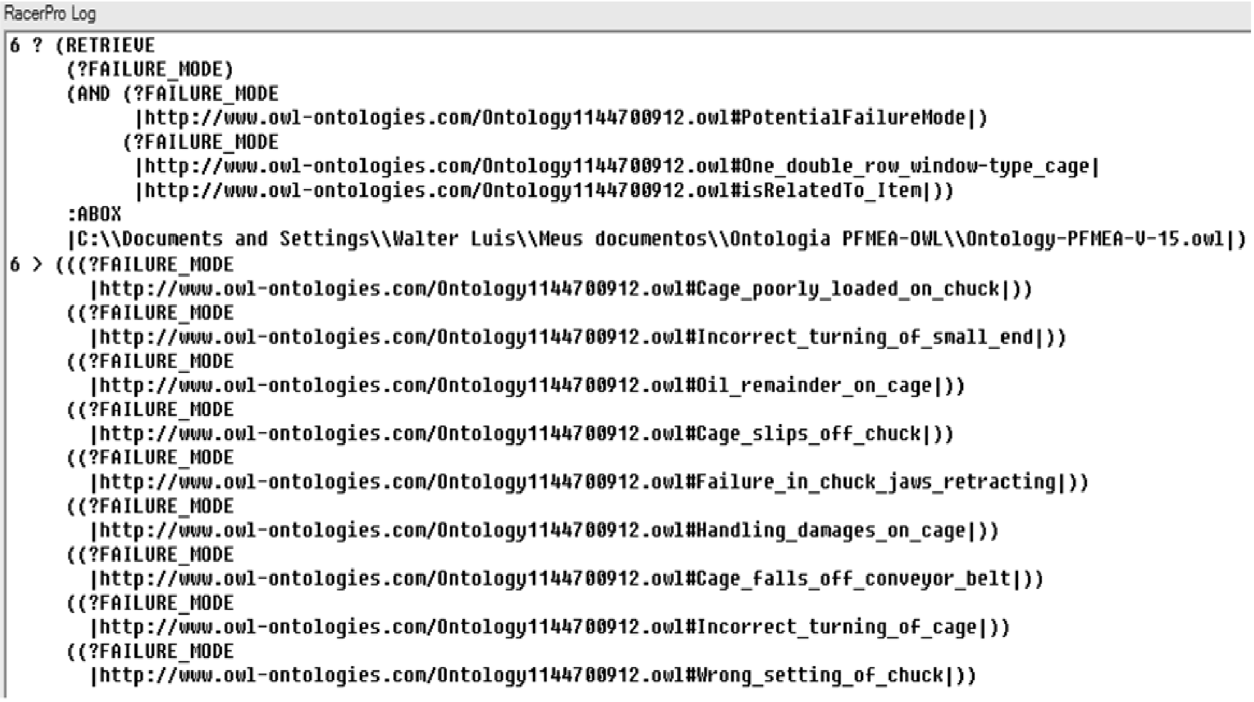
The evaluation of the functional dimension focuses on the intended use of the ontology and aims at evaluating the extension in which the proposed ontology represents the knowledge domain, which includes not only the available documents, but also the theories and practices adopted by a community[28].

The functional evaluation involved, initially, instancing the proposed PFMEA-DL ontology starting with a knowledge body (instances) 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 Six Sigma project, described by Lennartsson and Vanhatalo[29]. 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, roles and instances represented in the ontology in the OWL DL language with the cognitive model presented in the literature.

Additionally, an example of a role query atom from ABox perspective is presented in the nRQL language (figure 5). The objective of this query is to recover all the Potential Failure Modes identified during the analysis of the process of producing the part, in this case “One double row window-type cage”, which is an instance of the #ComponentLevel subclass of the class #SystemLevel).

In this example, the role query atom is looking for all explicitly modeled “#PotentialFailureMode and #One double row window-type cage” pairs in the PFMEA ABox, which are related by role (OWL Object Property) “#isRelatedTo_Item” and this role is declared in the associated TBox.

It is important to observe the OWL Object Property “#isRelatedTo_Item” was not modeled as a quantifier restriction to the PotentialFailureMode class as shown in figure 4, but alternatively by the specification of the property domain and range available in the OWL DL language, considered as axioms by the inference service, as it is shown in figure 6.



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RacerPro Log
6 ? (RETRIEVE
     (?FAILURE_MODE)
     (AND (?FAILURE_MODE
            |http://www.owl-ontologies.com/Ontology1144700912.owl#PotentialFailureMode|)
           (?FAILURE_MODE
            |http://www.owl-ontologies.com/Ontology1144700912.owl#One_double_row_window-type_cage|
            |http://www.owl-ontologies.com/Ontology1144700912.owl#isRelatedTo_Item|))
     :ABOX
     |C:\\Documents and Settings\\Walter Luis\\Meus documentos\\Ontologia PFMEA-OWL\\Ontology-PFMEA-V-15.owl|)
6 > (((?FAILURE_MODE
       |http://www.owl-ontologies.com/Ontology1144700912.owl#Cage_poorly_loaded_on_chuck|))
     ((?FAILURE_MODE
       |http://www.owl-ontologies.com/Ontology1144700912.owl#Incorrect_turning_of_small_end|))
     ((?FAILURE_MODE
       |http://www.owl-ontologies.com/Ontology1144700912.owl#Oil_remainder_on_cage|))
     ((?FAILURE_MODE
       |http://www.owl-ontologies.com/Ontology1144700912.owl#Cage_slips_off_chuck|))
     ((?FAILURE_MODE
       |http://www.owl-ontologies.com/Ontology1144700912.owl#Failure_in_chuck_jaws_retracting|))
     ((?FAILURE_MODE
       |http://www.owl-ontologies.com/Ontology1144700912.owl#Handling_damages_on_cage|))
     ((?FAILURE_MODE
       |http://www.owl-ontologies.com/Ontology1144700912.owl#Cage_falls_off_conveyor_belt|))
     ((?FAILURE_MODE
       |http://www.owl-ontologies.com/Ontology1144700912.owl#Incorrect_turning_of_cage|))
     ((?FAILURE_MODE
       |http://www.owl-ontologies.com/Ontology1144700912.owl#Wrong_setting_of_chuck|))
```

Figure 5. Result of the nRQL role query atom using the RacerPorter Interface

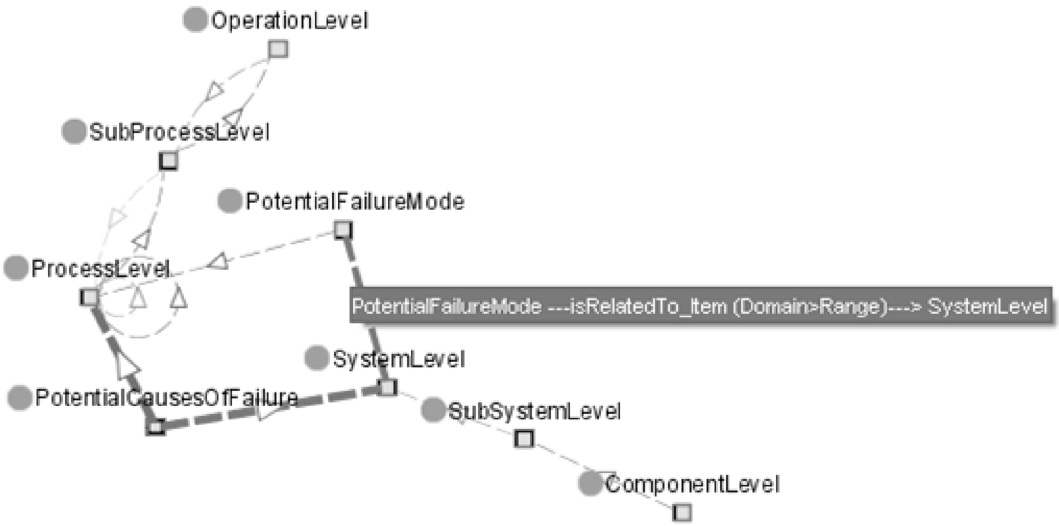

Figure 6. OWL Object Property Domain and Range - PROTÉGÉ OWL DL Editor Snapshot

However, the nRQL language allows the formulation of complex queries with regard to: concepts (classes), roles (properties), and constraint query atoms, as well as a combination of these, starting with query constructors. It also provides complex TBox queries to search for certain patterns of sub/super class relationships in taxonomy (OWL Document) [8].

4. CONCLUSION

This paper presented the development and implementation of the formal PFMEA-DL ontology based on the OWL DL standard ontology language recommended by W3C, seeking the computational interoperability of the knowledge base representation among different systems through the Intranet/Internet. From the conceptual point of view, the representation adopts concepts and terms widely recognized and of common sense in the quality context.

The use of concept elements allows the construction or import of product, process and function models, in agreement with the particularities of the companies involved in the manufacturing environment with distributed resources.

Finally, the PFMEA-DL ontology implemented in the OWL DL language and equipped with a formal semantics allows the knowledge inference and recovery between human or computer agents, as well as the support to the activities of management of organizational knowledge on manufacturing environments with distributed resources.

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