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Expert system based on ontological model to support the detailed design of agricultural machinery: a case of hydraulic hoses

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Abstract: A large amount of design information from different areas has become common in most organizations, this knowledge is dispersed in different formats and locations, and shared among different members of the design team; this fact hinders a synergic knowledge management and prevents its proper use by design engineers. Therefore, it is imperative that companies worry about the organization and adequate availability of this knowledge, by creating collaborative environments. In this sense, it is possible to associate the Knowledge-Based Engineering (KBE) approach. Through the concepts of KBE, this study proposes an expert system based on an ontology model to assist the decision-making process, from the storage and adequate availability of knowledge at the right time. Based on a literature review and a diagnosis made in a company of the agricultural machinery sector, the present work presents a solution able to meet the needs of its users (i.e. designers), as well as to improve the quality of decisions taken at the detailed design phase of a New Product Development (NPD) process. For that, a case of hydraulic hose design is explored. The application of the present proposal aims to facilitate the access to information, significantly reduce the appearance of failures along the NPD, as well as allow acquired knowledge to be used in subsequent projects (e.g., lessons learned).

Keywords: Knowledge-Based Engineering, expert systems, ontology, New Product Development, agricultural machinery.

1. Introduction

Currently, the industries are passing through a new period, considering a new approach called Industry 4.0. This approach assumes that, in the very near future, industrial production will be characterized by the high degree of product customization, supported by highly flexible, reconfigurable and agile manufacturing operations, easily adaptable to market demands and customer requirements (Blanchet et al., 2014).

Collaborative work is expected between companies and between them and their suppliers. Transparency in manufacturing, in the form of exchanges of information and resources through and between Smart Factories networks, can be considered a key concept (Lee et al., 2015).

Within Industry 4.0, Digital Manufacturing (DM) proposes the incorporation of technologies able to represent companies virtually (i.e., resources, equipment, people) to allow greater integration between product and process development through models and simulations (Chryssolouris et al., 2009). In order to relate the product definition to the actual production activities within the context of the DM, it is possible to consider the complete transformation of tacit knowledge into tangible and, finally, digital knowledge, optimizing data management and developing new standardized models (Chryssolouris et al., 2009).

However, in practice industries are still very far from this new concept. Engineering bi-dimensional drawings and textual documents are the most exploited means and still dominate the practice within companies, throughout the entire product life cycle. These information requires human reading and interpretation, which causes the appearance of errors and increase of time (Ivezic et al., 2014).

In the detailed design stage in particular, it can be pointed out that good design practices in the form of technical documents are dispersed in different places and formats (Subrahmanian et al., 2005; Chandrasegaran et al., 2013; Valilai & Houshmand, 2013), which hinders their use by project engineers. Failures (i.e., nonconformities) in products may occur due to the difficulty of access, time restrictions, or the way the information is made available. Important analyses can be skipped, and information may not be provided to subsequent design activities (Schmidt et al., 2016).

Neglecting information at the beginning of the NPD and the subsequent appearance of flaws increases rework Yassine et al. (2008), which makes design development longer. As presented by Ullman (2015), most of the manufacturing costs are associated with not using or misusing the information in the initial stages of the NPD. In order to make companies able to capture, organize and store knowledge, and allow them to be properly used in a collaborative environment, the so-called KBE approach can be successfully adopted.

KBE can be characterized as a set of solutions capable of assisting the development of engineering activities at different stages of the product development process, in the form of Knowledge-Based Systems (KBS).

KBE has large applications, is a technology based on dedicated software tools, which are able to capture and reuse product and process engineering knowledge, as well as a solution that can contribute to traceability, and search for knowledge, which guarantees a collaborative environment between users and allows the reduction of design time and costs of product development due to the associated automation aspect, converging on a global solution (Albarello et al., 2016; Mcharek et al., 2018, 2019).

Recognizing this approach, a literature review was conducted to find a relevant paper portfolio to support this work. This review was developed through the application of the ProKnow-C method (Ensslin et al., 2007, 2010). From this review, the most significant KBE-based solutions aiming at optimizing the execution of project activities have been selected. Some searches are tied to CAx (Computer-Aided Technologies) systems. Valilai & Houshmand (2013) propose a platform to help engineers to use product data and share information to facilitate the collaborative manufacturing environment. This tool is called XMLAYOD, an integrated collaborative platform based on the STandard for the Exchange of Product model data (STEP). For CAx system collaboration, the platform uses a solution aligned with the ability of the STEP standard to support XML (eXtensible Markup Language) data structures.

Monticolo et al. (2015) present a model called Knowledge Configuration Model (KCModel), which aims to improve the interoperability of different expert models by extracting crucial data and regrouping them into knowledge configurations. Thus, the main objective presented in this paper is based on the information embedded in geometric and simulation models for a centralized knowledge structure that can be shared and identified through a management configuration, avoiding errors especially in the initial stages of the design process.

According to Mcharek et al. (2019), the use of formal ontologies to represent knowledge related to project activities is also proposed. Panetto et al. (2012) use an ontology called ONTO-PDM to manage heterogeneous information through the conceptualization, formalization and construction of a product. The goal is to allow the exchange of information between systems, minimizing semantic uncertainties. Ahlers et al. (2015) present a system structure based on an ontology domain, aimed at providing information to users.

Imran & Young (2015), and Kim et al. (2006) point out the use of formal ontologies to represent assembly information mainly for the sharing of knowledge, establishing a taxonomy of concepts in this domain. (Chungoora et al. 2013) use a formal ontology to represent knowledge in the form of patterns, which, together with a computational meaning, brings higher expectations for an effective use of this information. The study conducted by Chang et al. (2008) presents a method to capture potential relationships in a large dataset through the use of an ontology, which allows the storage and reuse of knowledge.

Some studies employ the use of frameworks, such as those presented by Bermell-García & Fan (2002) and Igba et al. (2015). The framework presented by Bermell-García & Fan (2002) whose intention is to code and customize product development activities to automate the conceptual design process, as well as the framework presented by Igba et al. (2015) focused on managing the knowledge acquired through the use of complex products. Other searches are related to the creation of systems and tools. The work of Kaljun & Dolšak (2012) offers a smart counseling system aimed at providing knowledge related to the ergonomics design. Knowledge about the ergonomic design of a hand tool was collected, organized and codified in the form of rules of production, identified as rules of decision.

However, none of these works presents a solution able to be integrated into computational tools to effectively support product design (i.e., computationally implemented) and capture the knowledge in an unambiguous way from various sources and formats (e.g., standards, good engineering practices), capable of being a smart virtual mentor, providing qualified information for detailing components and subsystems from assumptions, requirements and design constraints. Recognizing this gap, the present paper aims to answer the following question: *"how to capture, organize and provide existing contextualized knowledge of product and processes to contribute to the development of products, from the perspective of DM?"*

The objective of this work is to develop a solution in the form of an expert system based on an ontology model, capable of meeting the users' needs (e.g. design engineers), as well as improving the quality of the project activities carried out over the course of the NPD. Through the provision of knowledge related to a particular product, this solution should assist in decision making by capturing, storing and making information available to stakeholders in the right measure, at the right time and for the right agents of the development process. The solution proposed was applied and evaluated in a real manufacturing environment, a multinational agricultural machinery company located in Curitiba, Paraná, Brazil. By means of on-site studies that are presented in detail later, in a specific component type, (i.e. hydraulic hoses), was defined as the focus of study.

This paper is structured in 4 section. Section 2 discusses the theoretical base necessary for an understanding of the work. Section 3 describes the methodological aspects considered. Section 4 presents how this work can contribute to the design of hydraulic hoses, through the demonstration of the results. This is done from the presentation of the development of the proposed model, its demonstration and evaluation.

2. Knowledge management in the NPD

It is known that the NPD is a process that demands intense knowledge. According to Owen & Horváth (2002), this knowledge is dynamic and alive. Throughout the NPD there are several information flows involving different areas. According to the NPD proposed by (Pahl & Beitz, 2007), much of this information accumulates in the final stages of the process (i.e., detailed design) (Chandrasegaran et al., 2013), as shown in Figure 1.

It is possible to present the NPD as an information network. Within this network, each participant or team collects the necessary input information, performs analysis, makes decisions, and then delivers exit information (Yassine et al., 2008). This information, when interpreted and reused, become knowledge. Due to Concurrent Engineering (CE) practices that aim to accelerate the development process, teams may consider information from preliminary requirements. (Yassine et al., 2008).

In this context, the so-called KBE approach has been defined by several authors, Bermell-García & Fan (2002), Chapman & Pinfold (2001) and Cooper & La Rocca (2007) as characterized by a set of solutions capable of assisting the development of engineering activities thanks to the systematic use of engineering knowledge, in the form of KBS. As a consequence, KBE has the ability to provide solutions that allow the automation and customization of design activities, by the combination of Object-Oriented Programming (OOP), Artificial Intelligence (AI), Computer-Aided Design (CAD) techniques, and technologies (Chapman & Pinfold, 2001; Verhagen et al., 2012; Pokojski et al., 2010, 2011a, 2011b, 2013; Pokojski & Szustakiewicz, 2012; Belkadi et al., 2012).

In addition, object-oriented KBE systems technologies allow the construction of object classes that contain several useful representations related to a product (e.g. geometry definitions, costs) Bermell-García & Fan (2002), which make knowledge explicit. Another feature of KBE is its ability to create structures to capture, store and reuse acquired knowledge (Verhagen et al., 2012; Belkadi et al., 2012).

Understanding the KBE concepts and methods proposed in the literature for the construction of valid solutions related to the development of a KBE application, it is known that one of the initial challenges is the elicitation and capture of knowledge (Schiuma et al., 2012). Hereafter, to allow subsequent use and traceability of the knowledge acquired through these methods, it is necessary to structure it. Among the different possibilities of representing and structuring knowledge, one is the use of ontologies. Ontologies have been employed in many researches, such as those presented by Imran & Young (2015), Kim et al. (2006), Chungoora et al. (2013), Rahmani & Thomson (2012), and Borsato et al. (2010).

According to Gruber (1993), ontologies can be defined as an explicit specification of a conceptualization and any knowledge-base or KBS is related to some kind of conceptualization, implicitly or explicitly. In addition, Staab & Studer (2013) refer to ontologies as a special type of object information or computational artifact. Computational ontologies can formally model the structure of a system

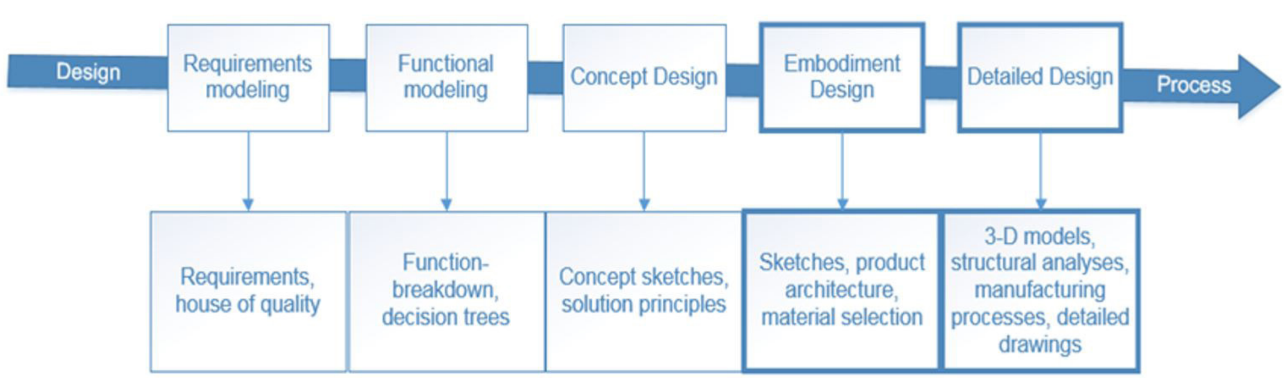

Figure 1. NPD steps associated with types of knowledge representation, adapted from Chandrasegaran et al. (2013).

(i.e. entities and relationships that emerge from these observations) and which may be useful for a particular purpose. To build ontology, a formal language is needed.

Based on Resource Description Framework (RDF), Web Ontology Language (OWL) is a Semantic Web language designed to represent rich and complex knowledge. Semantic Web purpose is to create documents that can be processed by both machines and humans (Berners-Lee et al., 2001). OWL has a well-defined syntax, which is a basic condition to allow machine processing Staab & Studer (2013). The study presented by Feilmayr & Wöß (2016) highlight the main benefits of ontologies: the principle of sharing by the semantic expressiveness of ontologies, the possibility of creating complex models and improving collaboration by providing a wide range of applications.

One way to implement ontologies is through expert systems (ES). ES are AI applications aiming to represent the expert knowledge and thus assist in decision-making activities and problem solving (Liao, 2005). They are often associated with KBS or considered equivalent (Nick, 2008; Sajja & Akerkar, 2010). AI associated with these systems allows both computers and humans to understand the knowledge expressed through them Rychener (2012), and their problem-solving ability makes it possible to make inferences useful to their users (Boose, 1985). When creating rules, it is possible to evaluate the data contained in a domain to achieve a specific goal (Abraham, 2005). The context and enlightened concepts served as the basis for the development of this work. Section 3 presents the research method considered and how this work was developed, from the presentation of the proposed steps.

3. Methodological aspects considered

3.1. The research approach

The present work is based on the Design Science Research (DSR) approach Simon (1996) and Peffers et al. (2007), which has been developed by several studies related to different fields, from natural sciences to design sciences, artificial sciences or design science. In the first case, the studies are related to how and why things happen. In the second, they are related to how things should be to reach a certain goal (Dresch et al., 2015). Thus, the main function of DSR is designing and developing artifacts or means by which a goal can be achieved (Simon, 1996).

According to such approach, artifacts can be defined as models, methods, constructs and instantiations. For the present work, a model is proposed to reach the intended goal. Models are a set of propositions or statements that express relationships between constructions (e.g. formal ontologies) that represent situations as problem and solution (Lacerda et al., 2013). They must be able to capture the structure of reality so that they may indeed be useful. In this context, DSR approach suggests a set of work phases that lead to the proposal for a consolidated, approved for use artifact (Figure 2).

Each of these phases are detailed as follows, according to Hevner & Chatterjee, (2010). Based on the ontology construction method, it is necessary not only defining the context to be represented, but also create competence questions so that, in the end, it is possible to evaluate if the ontology actually attends to what it was initially proposed (Grüninger & Fox, 1995). The literature review was chronologically performed after this stage. However, it corroborated with the definition of the objective and solution proposal, given the state of the art survey regarding the problem encountered.

According to Pinto & Martins (2004) the sequence of activities performed corresponds to: (a) specification; (b) conceptualization; (c) formalization; and (d) implementation.

To evaluate the proposed artifact, some criteria are prescribed by the methodological structure framework based on DSR, these correspond to the *fidelity* of the model with respect to reality, *completeness*, *robustness*, *consistency* and *level of detail* (Peffers et al., 2007). In order to evaluate the proposed solution, such criteria have been employed and thus, both the views of its developers (i.e. researchers) and

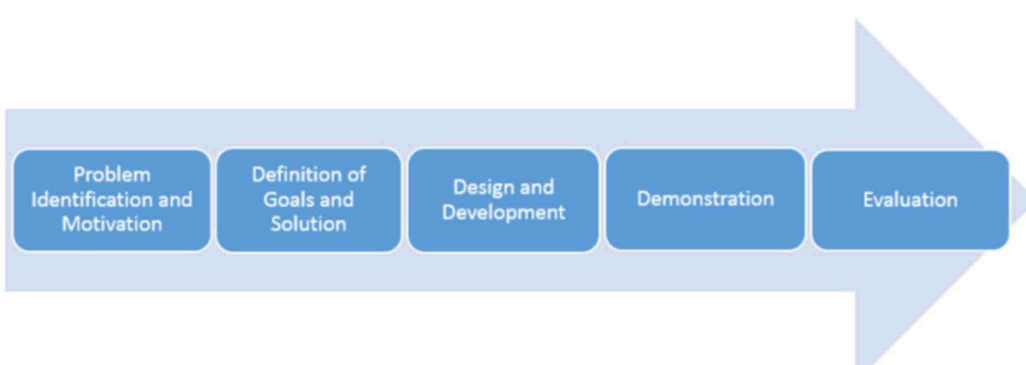

Figure 2. Methodological structure framework based on DSR approach, adapted from Peffers et al. (2007).

that of their potential users (i.e. design engineers) were appreciated.

The research has been consequently organized in the following phases, as described in the following section:

(1) Problem diagnosis;

(2) Solution design;

(3) Solution development;

(4) Solution demonstration;

(5) Solution evaluation.

3.2. Solution development and evaluation

3.2.1. Problem diagnosis

In this phase, a strategy based on a diagnosis performed in the agricultural machinery company, considered in this study, was conducted. The diagnosis was conducted in the company environment and lasted about 45 days. During this period, the documents related to the NPD of the specific company were evaluated to find possible inconsistencies. Meetings with several areas (e.g., Product Engineering, Manufacturing Engineering, Quality Engineering, Product Support) were carried out as well as the Engineering Change Order (ECO)s of the product being studied (e.g., tractor).

The ECOs related to the tractor were collected and classified according to the type of problem, (i.e. assemblability problems), ergonomics, among others. Also, interviews were conducted with the applicants and those who were supposed to make the change or who were related in some way. An interview script was used to assess the reasons that led to the emergence of the problem and to track the flow of information. From the evaluation of ECOs and interviews, it was possible to highlight the most recurrent problems, as presented in Table 1.

From the evaluation of the problems as highlighted in Table 2, it was found that the majority of them was associated to the missed or inadequate use of information in the Detailed Design stage, originating from good design practices, documents or experience with past projects, given the problems recurrence. As reasons for not using the information, designers highlighted as the main factor the lack of time, forcing them to leave aside important considerations.

Consequently, not considering information reflects on problems in later stages of the NPD, which require much greater efforts to be solved. Given this, a research opportunity was found and, as presented in 3.1 section, of methodological aspects, a solution was proposed. To develop such a solution, based on the evaluation of ECOs presented earlier, the context of hydraulic hose design was considered. Documents related to this context were collected and interviews with members of the company's hydraulic team were conducted. The following section presents what has been accomplished during the development of the proposed solution.

3.2.2. Solution design

In this phase, it was decided that the designers could benefit from an ontological model. From the sequence of activities presented in 3.1 section, foreseen by Method 101,

Table 1. Problems encountered due to project failures.

Product failure	Requesting area
Mechanical interferences	Manufacturing
Electric harness paths difficult assembly, or collide with parts or mechanisms	Field testing
Disconnection of hydraulic hoses	Customer
Service brake and clutch requiring excessive user effort	Manufacturing
Cracks in welded joints	Customer
Difficulties of access for maintenance	Prototyping
Problems related to product efficiency (e.g. torque, braking)	Customer
Absence of holes or slots necessary for assembly	Prototyping
Electrical systems failure (e.g. oil pressure indicator light not lit)	Customer
Cabin air conditioner malfunction	Customer

Table 2. Research scenarios.

Application (scenarios)	Input data
Gear Pump	Flow rate = 20 to 50 L/min (liters per minute) Maximum working pressure = 21 MPa (megapascal) Burst pressure = 84 MPa
Hydrostatic Transmission	Type of hose used in the USA = class 100R13 Burst pressure = 34.5 MPa Relief valve maximum pressure = 42.5 MPa

it is initially necessary to define which domain should be represented. This domain was defined through the diagnosis performed in the company, which was presented previously. In order to build the ontology, the definition of its scope is a fundamental step. In order to define the main purposes on the ontology, a set of focus groups with members of the company hydraulics team were carried out. In this way, it was possible to identify what knowledge needed to be known before a hose could be selected.

The moderator requested to hydraulic engineers to depict some use scenarios and, through these, competence questions were defined. The combination of the scenarios and the questions allows the solution to be demonstrated and evaluated at the end. Table 2 shows the use cases considered.

In the first scenario, the gear pump can deliver from 20 to 50 L/min and the system can reach a pressure of 21 MPa. At maximum flow rate, the fluid velocity reaches 5 meters per second (m/s) and the minimum velocity is around 2.5 m/s. So that there was not much loss of load in high flow and to be able to present good operation in low flow, it was opted for a hose with diameter of 10 mm, class SAE 100R17. The diameter is obtained by applying the following Equation 1 (Brunetti, 2008):

$$Fluid\ velocity\left(m/s\right) = 21.2 \times \frac{Flow\ Rate\left(l/min\right)}{\left[Hose\ Internal\ Diameter\ ID\left(mm\right)\right]^2} \quad (1)$$

Besides meeting the minimum requirements, such as bursting pressure and diameter, this hose was chosen because it presents a bend radius smaller than the others and because it is normally used in the company, which facilitates its adoption.

In the second scenario, the hydrostatic transmission with a SAE 100R13 class hose (related to a product originated in the United States, which was brought to Brazil) meets up to 34.5 MPa of working pressure. However, the system in which it is inserted has a relief valve with a capacity of 42.5 MPa of working pressure. Due to the conditions under which the product can be subjected in Brazil (e.g., steep climbs), it would be possible for the system to reach the maximum valve pressure. Thus, before presenting problems in the field, the hydraulics team suggested replacing the hose by another one, now of the class SAE 100R15. It is important to note that the working pressure is equivalent to a quarter of the hose burst pressure.

In view of this information, the sequence of activities performed by design engineers and the evaluation of standards used by them, it was possible to create competence questions, necessary for the construction of the ontology. The issues are as follows:

(1) What is the application of a hose X?

(2) For a given condition of pressure P and diameter D, which hoses can be used?

(3) For a given condition of pressure P and diameter D, what are the costs of the hoses that can be used?

(4) For the use case Z, which applications were (not) successful?

The unknowns X, D, P and Z are described in this way because they must be later replaced by values in this work. Recognizing the context of hydraulic hose design, a search was conducted in online ontology databases and Defense Advanced Research Projects Agency "DARPA" Agent Markup Language (DAML) Ontology Library (DAML Ontology Library, 2016) and Directory Mozilla DMOZ (DMOZ, 2016) to identify possible ontologies that could be reused. No useful ontology was found, that is, building a complete model would be necessary.

The next step is the evaluation and interpretation of captured knowledge. This must be done so that later it is possible to transform such knowledge into ontology entities (e.g. classes, properties, individuals). The domain of defined knowledge was initially structured as a conceptual model, in the form of mind maps. Figure 3 illustrates the representation of part of a standard as an example. This standard presents types of classes of hydraulic hoses, each associated with classes of SAE J517 and J30 standards. In addition, technical characteristics of each type of hose are defined, such as dimensions, materials, working temperature, pressure, among others. This phase allowed to normalized knowledge for the following solution development.

3.2.3. Solution development

In the "Design and Development" phase, the proposed artifact is based on the method presented by Curran et al. (2010) for the development of KBE solutions. It is necessary to present also the method of ontology construction adopted in this work. Presented by (Noy & MacGuinness, 2001), the method of constructing ontologies called 101 was considered.

For solution development, the knowledge collected and initially described in natural language was restructured, being represented in the subject - predicate - object form (e.g., Pressure 1 - has a pressure of - 1 MPa). In addition, the taxonomy of the ontology model was defined. At this stage, the Protégé (2016) ontology editor was used. For its construction the following classes were created: *Product*, *ProductHistorical*, *ProductPart, ProductProperty* and *ProductSupplier*. The representation of this taxonomy with the main classes and subclasses is illustrated in Figure 4.

The class called *HoseHistorical* contains information related to the history of hoses used in different use cases that, in this work, are related to the scenarios presented previously. For this purpose, individuals were created

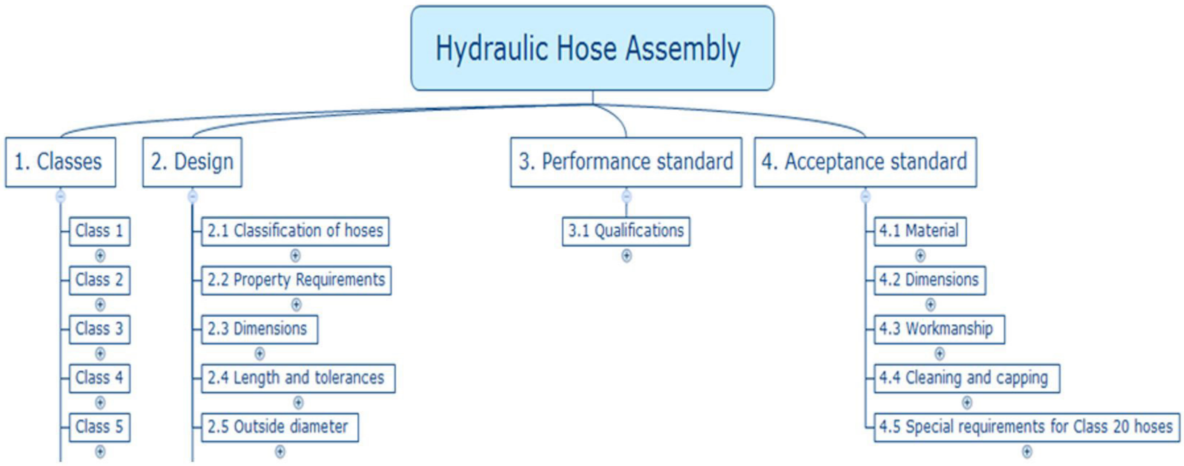

Figure 3. Representation of a mind map through software XMind.

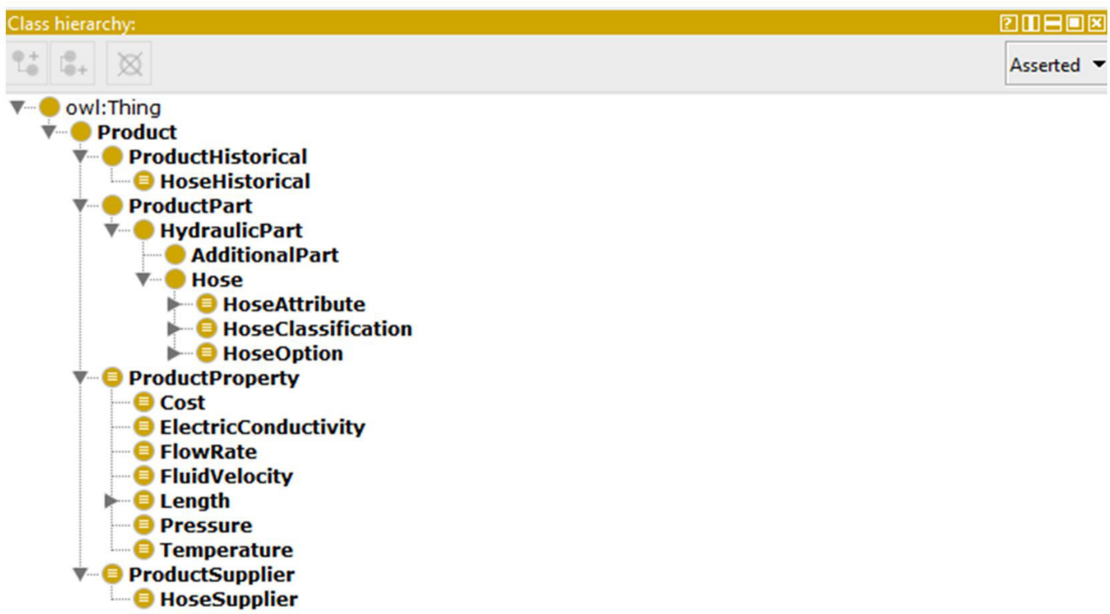

Figure 4. Class taxonomy of the proposed ontology model in the Protégé editor.

to represent each of the use cases, as can be observed in Figure 5. The *ProductPart* class represents components that belong to a product, in the case, *AdditionalPart* and Hose. The first corresponds to identify additional hydraulic components needed to define this ontology. The second is characterized by information and knowledge necessary to define a hose, such as its attributes (i.e. *HoseAttibute*), its classification (i.e. *HoseClassification*), and hose options that may be used (i.e. *HoseOption*).

The *HoseOption* class has two subclasses, *HoseAvailableOption* and *HoseAvailablePerSupplier*. The first one is intended to represent possible hoses available in the company, as explained in Figure 6 and 7 shows the example of an individual of class *HoseAvailableOption*. The second, *HoseAvailablePerSupplier* class corresponds to the allocation of costs to hoses, based on possible suppliers. Actual suppliers of the company were contacted to obtain this information.

However, only one supplier returned information when requested, which made it impossible to represent costs reliably. Figure 8 shows one of the individuals created in the *HoseAvailablePerSupplier* class. The *ProductProperty* class corresponds to the properties necessary to define and create the present ontology (e.g., pressure, length). *HoseSupplier* class aims to represent potential hose suppliers of the company. This information is required because of its

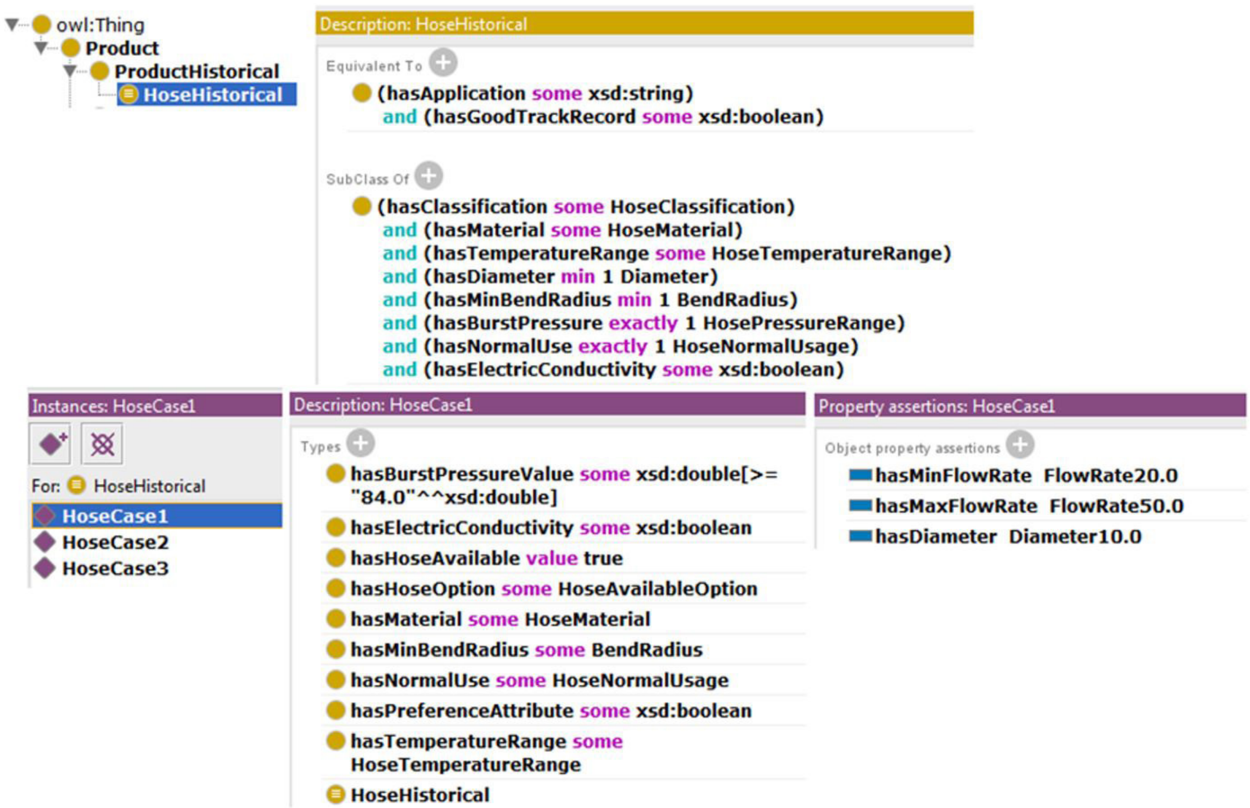

Figure 5. Definition of *HoseHistorical* class and *HoseCase1* instance.

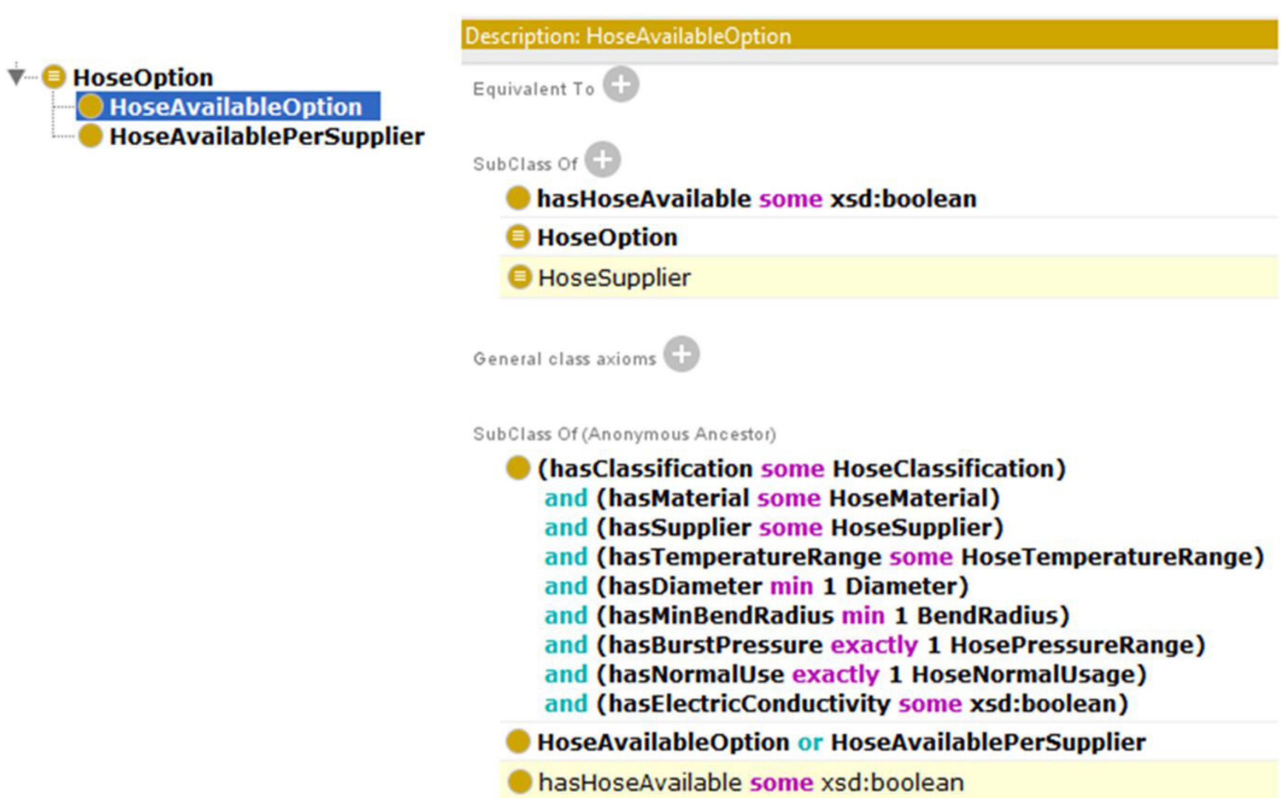

Figure 6. *HoseAvailableOption* class description.

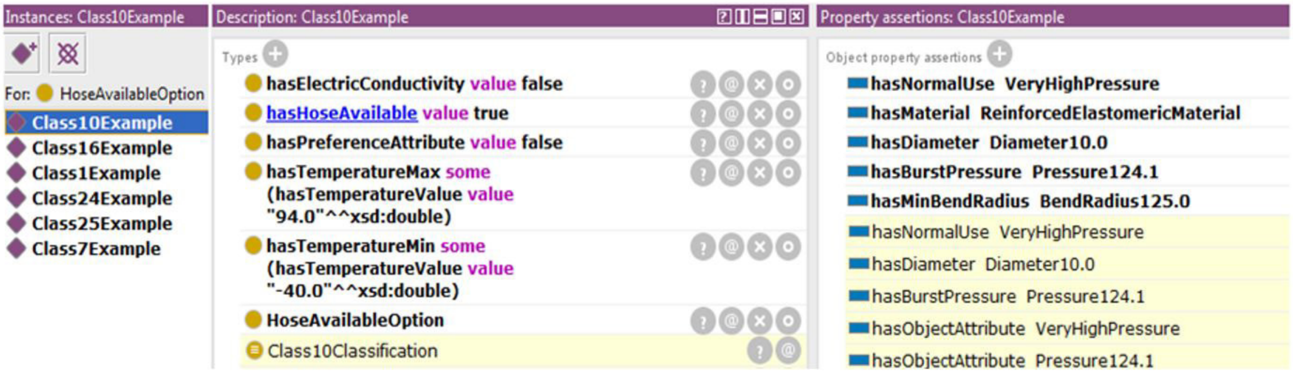

Figure 7. Example of an individual of class *HoseAvailableOption*.

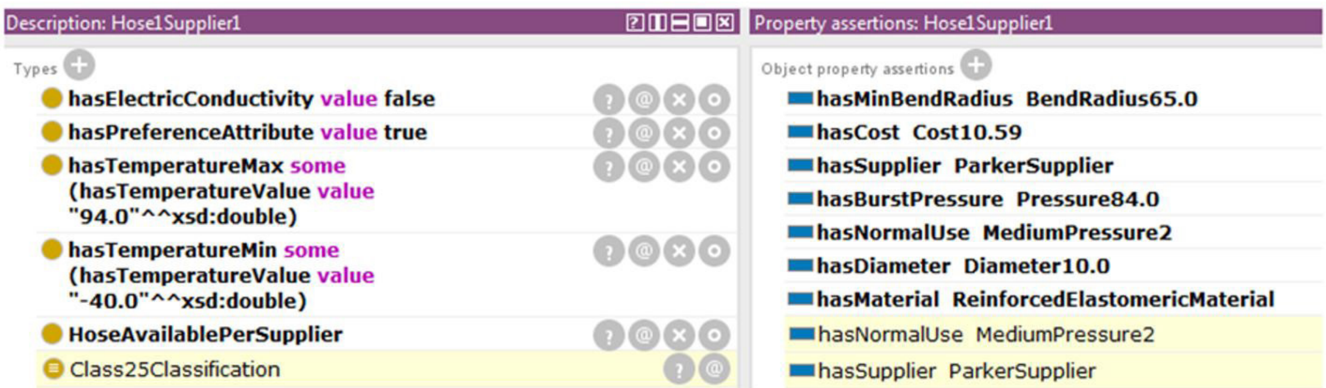

Figure 8. Hose1Supplier1 instance from *HoseAvailablePerSupplier* class.

association with costs. It is important to emphasize that taxonomy, individuals and properties have changed and have been readapted many times throughout development, always to achieve a better representation of the domain.

To verify possible inconsistencies and perform inference in the model, one of the Protégé reasoners called Pallet was used. A "reasoner" evaluates if there is any contradiction in the ontology, comparing tested classes with the resulting knowledge-base (Parsia et al., 2005). The results of this evaluation indicated that no inconsistency was found in the proposed model. Furthermore, the information was inferred by the reasoner. One of the greatest benefits of ontological models is the ability of the model to understand the relationships existing between such entities through information attributed to individuals or classes. A set of queries has been elaborated to identify if the created ontology model answers to the initial problem questions.

3.2.4. Solution demonstration

The demonstration step started with the search for valuable implementation solution. The first considered tool was Protégé Snap-SPARQL plug-in; subsequently (Stardog, 2017) platform was adopted. Among the platforms available in the market, capable of manipulating graph databases, Stardog was selected due to the fact of presenting free licenses, as well as the knowledge needed to use it. However, platforms like Neo4j could also have been employed.

Scenarios were the key to the design, demonstration and evaluation of ontological models, as presented in the paper by Grüninger & Fox (1995). According to these authors, scenarios can be described as historical problems or situations that cannot be associated with existing ontologies. In view of this, the two scenarios proposed by the company engineers, previously presented, were considered. From these real cases, some queries were carried out in order to identify if the ontology model would be able to answer possible questions of the engineers in a satisfactory way. These queries are based on the competence questions defined in 3.2.2 Section.

3.2.4.1. Queries

To identify whether the ontology created would be able to return desired information, the Protégé Snap-SPARQL plug-in was used. A query always consists of two parts, SELECT and WHERE. The first one, SELECT, identifies the variables that should appear in the search result.

The second, WHERE, represents the basic pattern of graph databases, that is, in the form of triples (i.e., subject, predicate, and object). The query illustrated in Figure 9 is associated with Competence Question 1, that is, it aims to demonstrate that the ontology can point out the application of a particular hose available in the company. The hose, here represented by the individual *Class10Example*, is associated with a property that relates to an application or use (i.e. *hasNormalUse*). Thus, the variable that contains this information, represented by *HoseNormalUsage*, must be the result of the query.

As can be seen, the *Class10Example* hose is normally employed when a very high pressure (i.e. *VeryHighPressure*) is considered, with values above 350 MPa burst pressure.

Another query represents Competence Question 2, which corresponds to identifying which hose can be used, knowing the values of diameter and pressure. Thus, this search returns which hoses available in the company have a diameter equal to 10 mm and that meet a burst pressure greater or equal to 84 MPa. The answer obtained allows the design engineer to evaluate, among the possible hoses presented (*Class25Example*, *Class24Example* and *Class10Example*), which would be the most appropriate. As can be seen in Figure 10, the hoses that could be used are associated with the respective bend radius and hose burst pressure. Most of the time, engineers give preference to those with a lower bend radius. Such information is exposed in the query result.

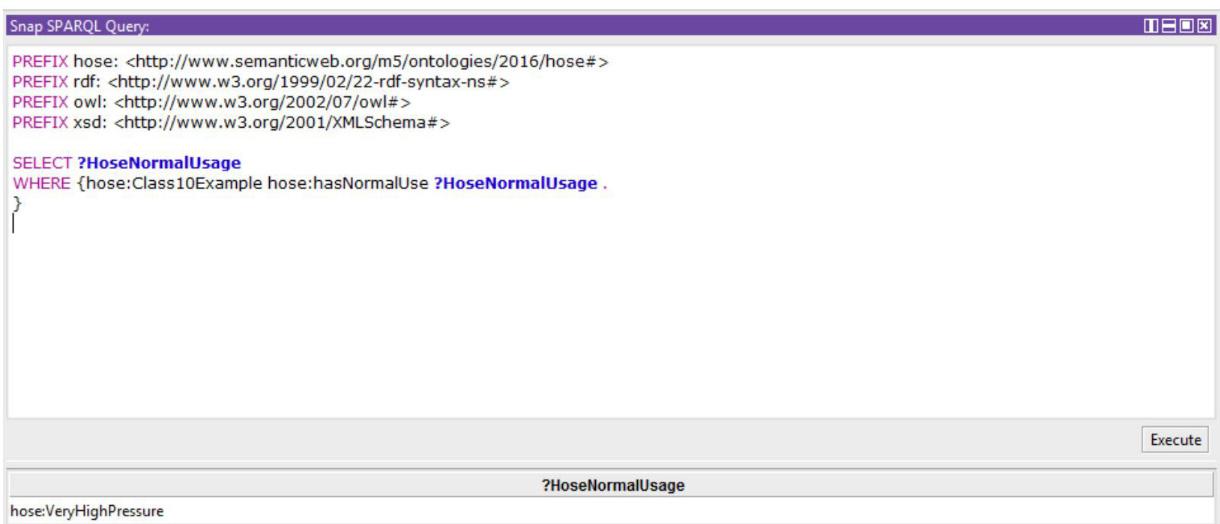

Figure 9. Query result using the Snap-SPARQL plug-in regarding Competence Question 1.

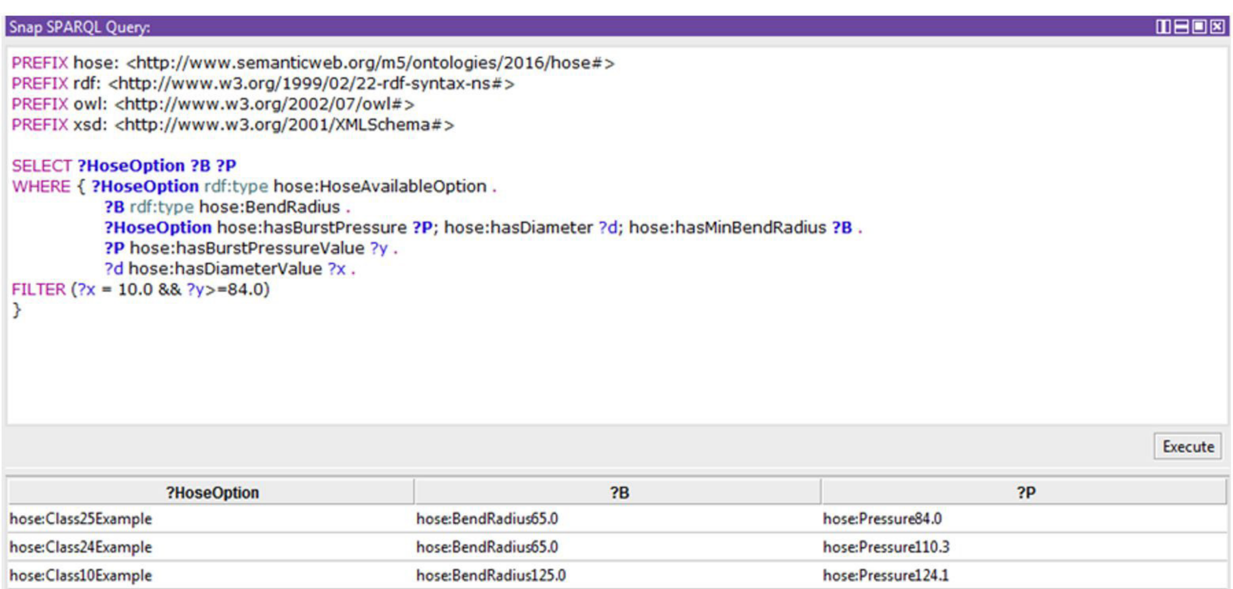

Figure 10. Query result using the Snap-SPARQL plug-in regarding Competence Question 2.

The other competence questions were executed in the same way and returned the desired information. These are presented in the next section, through the Stardog platform.

3.2.4.2. Stardog

All previous queries, implemented into the Snap-SPARQL plug-in, were performed on the Stardog platform. Stardog allows performing queries in databases in RDF, in a much faster way than through Protégé. This is due to some of its characteristics, such as its graph semantics, data modelling and the use of deeper reasoning. Stardog also allows saved databases to be available to other people, on other computers and locations. They can edit, view, or perform searches according to permissions that can be assigned to each user.

Another relevant feature is that platforms like this allow the use of information and data from other existing databases, in the form of a Federated Database System (FDBS), which is basically a system that has different components (i.e. databases) that cooperate with each other (Sheth & Larson, 1990). Thus, to insert the ontology model as a database in this platform, initially a file in RDF was created from the OWL used in Protégé. The creation of the base is a simple process, that is, a user with little experience can do it since it presents a previously defined default configuration. After creating the base, the queries were done according to the same structures presented previously, since this platform uses SPARQL language. The following are some of the queries that illustrate how the user interface is.

Figures 11 and 12 represent Competence Questions 3 (Cost) and 4 (applications were (not) successful). The results obtained using Stardog and Protégé plug-in were the same, which justifies the adoption of this platform, mainly because of the more satisfactory performance in terms of response time.

Once the artifact demonstration stage is completed, the next step corresponds to its evaluation, a very important step within the sequence of DSR activities.

3.2.5. Solution evaluation and results discussion

This section presents the details of the evaluation step. A classification based on variables and values was performed. Based on the context of the present work, only some of these variables and values are considered and each of them is explained in Figure 13.

The variable approach represents which features of the object (i.e. artifact) are evaluated (e.g. facts, claims and assumptions) (Cleven et al., 2009). The approach is divided into quantitative and qualitative evaluation. The former uses numerical analyses to illustrate the relationship between factors and the phenomenon studied. The latter corresponds to characteristics of the object that are not evaluated on a numerical basis, but rather a value base that emphasizes the description and understanding of a situation behind the facts (Chen & Hirschheim, 2004). Thus, it is considered that this work must be evaluated qualitatively, as it aims to evaluate if the real context is represented through the proposed model.

According to the captured knowledge and delimitation of the scope of the model, the developed ontology actually

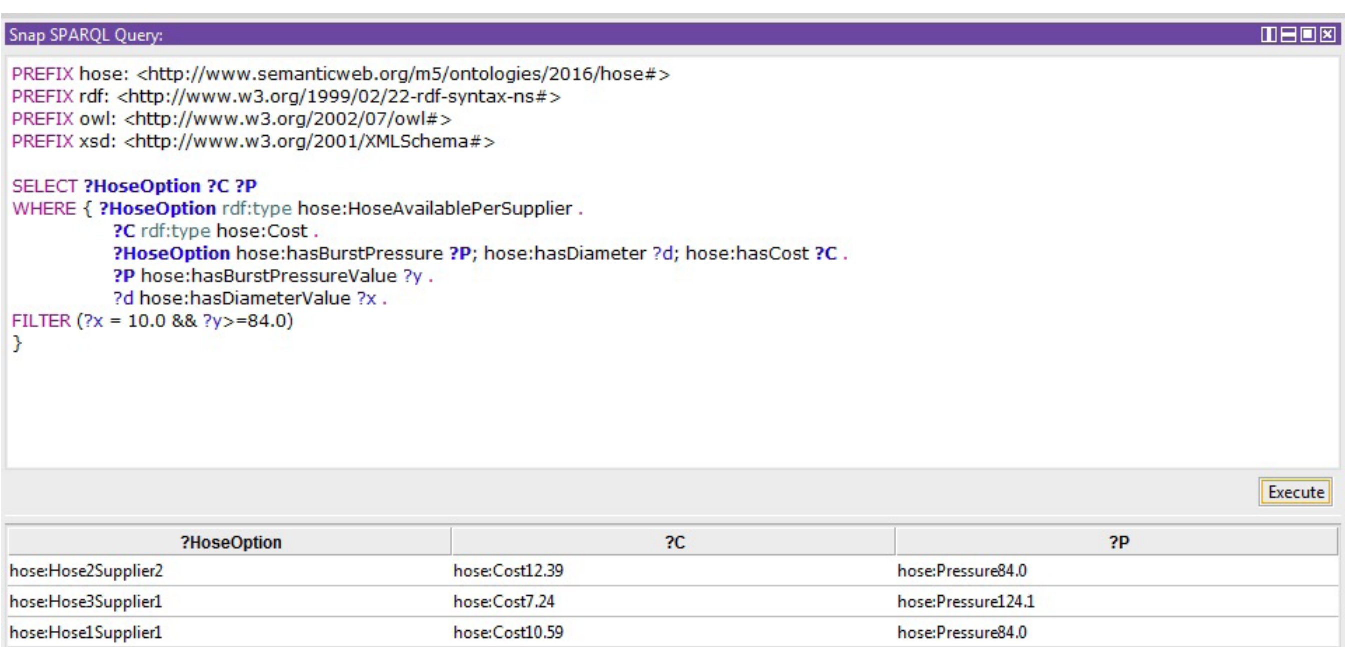

Figure 11. Query performed on the Stardog platform regarding Competence Question 3.

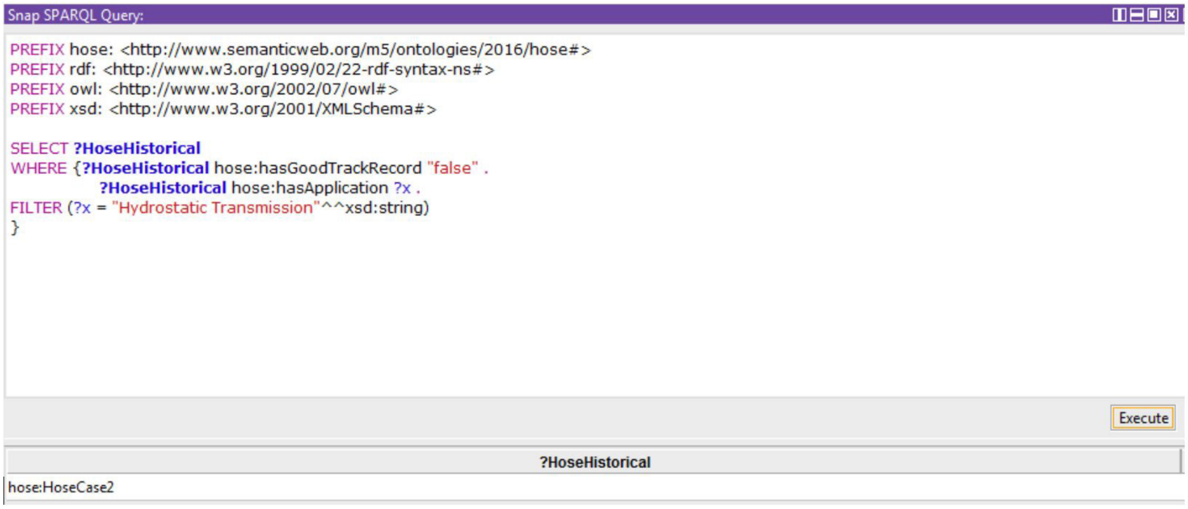

Figure 12. Query performed on the Stardog platform regarding Competency Question 4.

Variable	Value				
Approach	Qualitative		Quantitative		
Type of artefact	Constructs	Model	Method	Instantiations	Theory
Perspective	Economic	Deployment	Engineering	Epistemological	

Figure 13. Variables and Values to evaluate artifacts. Adapted from Cleven et al. (2009).

represents the context of hydraulic hose design. In addition, one of the techniques considered about “descriptive evaluation” is the form proposed by (Hevner & Chatterjee, 2010). This technique seeks to demonstrate the usefulness of the artifact developed, which can be done by constructing scenarios. These were used in the demonstration stage and through them it was possible to present that the ontology model was able to answer questions raised by the company’s engineers.

According to Grüninger & Fox (1995), competence questions not only guide the construction of ontological models but are also used in the evaluation stage to identify if the model actually meets what was initially proposed. In addition Frank (2007) brings another variable such as perspective and argues that an objective assessment is difficult to achieve. Given this, the variable is subdivided into Economic Perspective, Deployment Perspective, Engineering Perspective and Epistemological Perspective. Among these values, Deployment and Engineering Perspective stand out, being the ones that best represent the present work.

The first one, Deployment Perspective, considers aspects of understanding, appropriateness, and acceptance. It means that the model must be understood by all stakeholders, so that it must describe all its concepts in a familiar way so that users can actually use it (Frank, 2007). The Engineering Perspective addresses how the artifact is constructed (e.g. modeling or programming languages used, degree of description of components) as well as the definition and explanation of the artifact in view of the initially proposed objectives. An assessment based on these two perspectives should be directed not only to the artifact developer, but also to potential users.

With regard to the developers’ perspective, it is possible to state that the OWL language used to construct the ontology is a widespread language, capable of representing rich and complex knowledge and the relations between this knowledge Grüninger & Fox (1995), Uschold & Gruninger (1996) and Bechhofer (2009). In addition, it can be stated that there is no inconsistency within the ontology model, due to the use of the reasoner Pallet that did not indicate the presence of errors. Searches were also performed to demonstrate what information could be obtained (i.e., demonstration step). In order to identify the users’ perspective, the model was presented to the company design engineers. After that, a questionnaire was made available to these users (i.e. Table 3) to identify each user’s opinion.

Table 3. Questionnaire delivered to company engineers.

Questionnaire
1) Does the ontology model represent the context for the design of hydraulic hoses? If so, how much does it represent?
2) Would it be possible to adapt this model to another scenario/component?
3) Is there any contradiction with regard to structured knowledge?
4) The ontology model can be considered well detailed?
Likert scale:
(1) Totally agree
(2) Agree
(3) Not agree or disagree
(4) Disagree
(5) Totally disagree

According to the Likert (1932) scale, from the answers obtained during the evaluation:

i. it is possible to state that the proposed model successfully represents the context of design of hydraulic hoses. However, in order to fully represent it, more information and knowledge still needed to be inserted;

ii. The answer was positive regarding the adaptation of the model to other components or scenarios;

iii. Regarding the existence of contradictions in the model, they answer that it would not be appropriate to state whether or not there was some kind of contradiction. However, the use of the reasoner suppresses this point; and

iv. The engineers replied that, in terms of detail, they considered the model well detailed (i.e. accordingly), given the definition of the scope.

Furthermore, it is possible to correlate this information obtained with the evaluation to the DSR criteria. The representation of the hydraulic hose design domain can be associated to the model's *fidelity* criteria with respect to reality and *completeness criteria*. Given this, it is possible to state that the model represents the proposed domain. However, according to the questionnaire, it is possible to state that more knowledge could be inserted.

The *robustness criterion* is associated with the ability to adapt the model to other components or scenarios. Such an adaptation is feasible, since the model was created taking such adaptation into account. Through the use of the reasoner, it is possible to verify the *consistency criteria*, since this is associated with the existence or not of contradictions in the model. According to what was initially proposed, it is possible to state that the model is detailed, as far as the *level of detail criteria* is concerned. It is important to emphasize that the evaluation of models is a step that, if desired, can be carried out in different ways and comprise several conditions, in a much more complex way than what was presented in this section.

4. Conclusions

To meet the demand for knowledge provision during the Detailed Design phase, an ontological model was presented. This model assures the structuring of the knowledge of a given domain, defined herein as the context for the design of hydraulic hoses. The knowledge associated with this domain was captured and structured through the construction of the proposed taxonomy.

In addition, object and data type properties were created to relate classes to other entities. Once the ontological model was constructed, questions defined at the beginning of the solution development stage were performed in the form of queries. This was done initially by using the Protégé Snap-SPARQL plug-in. After that, the same queries were performed on the Stardog platform. The union of a database (i.e., from a file in RDF language), the performance of an inference engine (i.e., reasoner) and a user interface that makes up this platform, allowed to state that this can be considered an expert system, from the point of view of its constitution.

From the demonstration and evaluation of the model, it is possible to state that the proposed solution is relevant and could help the engineers in the execution of their activities.

Such a solution allows for faster availability and use of acquired knowledge, bringing benefits such as the reuse of knowledge in future projects, as well as a possible reduction of ECOs. Thus, this study shows the potential union between ontological models and expert systems to achieve a structure that is truly capable of meeting the needs of design engineers. From this association, it is possible to develop solutions capable of creating collaborative environments, that contain knowledge of different areas and that are in different formats.

In addition, the present research may be used as a starting point to support the design of other important machinery components, as the results obtained with the use of ontology models are promising and therefore could be integrated in the development of complex systems. The present work presents important insights not only regarding the construction of other ontology models, but also on the expansion of the present one to include more components and subsystems.

Nevertheless, the construction of an ontology model is a challenging activity. The model developed for hydraulic hoses has been changed several times to better represent the domain of knowledge without generating inconsistencies. Among the changes are the definition of taxonomy and axioms that best represent the domain, as well as the creation of properties and individuals appropriate to the context. In addition, the process of constructing ontologies demands iterations, that is, it is often necessary to return to the already implemented steps and redo them to better adapt the representation of the domain.

Among the limitations of the paper, it is possible to mention the difficulty of using reasoners in the Protégé ontology editor. Increasing the complexity of the model, by adding individuals and properties, prevented the tool from working faster. Thus, it is possible to state that Protégé's performance is somewhat limited when a more complex ontology is created. The use of the Stardog platform, however, proved to be much safer and more satisfying. Another limitation is related to the proposed expert system, whose initial objective was to present a user-friendly (i.e. company engineers) interface. The presentation of the queries to the design engineers brought this question, given the need to know the SPARQL language. Therefore, as a continuation of this work, it would be pertinent to develop a more user-friendly interface, where the user would identify or create questions in natural language, obtaining answers in the same way.

As future work, further detailing of the hydraulic hose design domain can be accomplished, and a more complex use case will be modelled. Information related to terminals and sealings are some of the examples that could be considered. The adoption of this model for the structuring of knowledge related to other domains (e.g. design of electric harnesses, transmission) is also a continuation alternative. In addition, building a friendlier interface, as mentioned earlier, would be a good opportunity for later work.

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