Ontology Driven Certification of Pressure Equipments

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Standards and engineering codes rule design, construction and operation of chemical plant equipments to ensure reliability and safety. In this article, we exploit knowledge-based methodologies and technologies to guarantee safety rules compliance of pressure equipments. Specifically, we describe a knowledge-based tool defined on top of a knowledge-based computer-aided design system, which can serve inspection bodies, i.e., for certification purposes, and pressure equipment designers for the verification of the appropriate safety normative (i.e., the pressure equipment directive). The article focuses on the knowledge base of the tool, which has been formalized through the PED&I (Pressure Equipment Design and Inspection) ontology. The ontology has been enriched by logical axioms, which ensure the consistency of the knowledge base, and by reasoning rules, which enable to infer new relationships among the class instances stored in the ontology. © 2008 American Institute of Chemical Engineers Process Saf Prog 27: 313–322, 2008

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INTRODUCTION

Safety plays a very important role all through the life cycle of a process plant, from the process design phase to engineering, construction, operation, maintenance and revamping phases. Incorporating reliability and inherent safety principles into a plant design requires thorough attention to design details, including the systematic review by a multidisciplinary team of process and equipment experts [1]. In particular, the increasing awareness of safety and economical issues strengthens the needs of more secure and reliable engineering equipments, which may cause problems because of different reasons, such as incorrect design or realization, improper installation or use, or inadequate maintenance. Consequently the design, manufacturing and installation of plant equipments and machineries are subjected to laws to warrantee they are safe and will not affect people’s health.

Indeed, equipments, such as pressure vessels, tanks, reactors, boilers, pumps, and valves have to meet complex safety requirements and criteria, which may be quite difficult to assess in the design phase. To this aim, in the past decades professional institutions and trade associations developed engineering codes and standards, which cover the design, the construction, the maintenance and the inspection of a wide range of equipments. Codes are widely applied in process industry to realize safe plant components and to meet the overall plant safety criteria. The adoption of appropriate standards and codes for the employment and the maintenance of plant equipments, which operate in a major hazard establishment, is a crucial issue for the assessment of the safety, as required by the “Seveso II Directive” [1].

Decisions taken at the beginning, i.e., during the detailed plant design, influence reliability and safety, and may imply later plant changes, such as adding external safety measures. Therefore, in current practice designers have to comply with the safety criteria since the very first design phases, to avoid errors and waste of time in the subsequent design and approval phases. Then, as required by National and International regulations, technical bodies have to verify the safety criteria adherence as soon as they receive the drawings, to speed up the approval process.

Nowadays, computer-aided design (CAD) systems support designers in every phase of the process plant...
development. Initially developed to handle just geometries, they have become sophisticated tools, able to manage all the aspects of engineering design: shapes, geometric features, functions, constraints, relationships and standards. In particular, commercial systems offer workbenches and functionalities for knowledge-based engineering (KBE). KBE offers an enhanced support for the description and processing of product models in the whole product lifecycle, and enable to computerize several types of knowledge: geometric data, technical specifications, normative and standards, and best practice guidelines deriving from past experience. Knowledge-based CAD systems (KB-CAD) allow users to define and manage rules, which may assure that the designed parts automatically adhere to a priori defined rules. Furthermore, a KB-CAD may handle parts previously designed, and may verify the compliance with the rules defined also a posteriori, highlighting possible incoherencies. The ability to computerize geometric rules results in faster and higher quality design. However, a KB-CAD is able to manage only detailed and well-defined geometrical rules, but it cannot handle indirect criteria. Thus, KB-CAD are not sufficient to provide a thorough support for the verification of the safety compliance of CAD models, e.g., of chemical plants and equipments.

The objective of the research presented in this article is the definition of a knowledge-based (KB) design system supporting on the one hand designers in the application of safety rules for plant components since the first design stages, and on the other hand inspectors which verify the normative compliance of pressure equipments models. Hazard situations deriving from safety rules violations can be avoided, thus providing a fundamental capability to support organizations that perform plant safety certifications. To formalize the expert knowledge related to this domain, we designed a Pressure Equipment Design and Inspection (PED&I) ontology. We focus in particular on the formalization of the appropriate safety normative pressure equipments have to comply with. Specifically, the application supports the safety rules of vessels for the storage of under-pressure fluids according to the pressure equipment directive 97/23/EC, as they are applied in Italy, where they are encoded in the VSR collection.

The addressed application may benefit from the ontology we propose in different aspects. First of all, ontologies are used to formalize a shared conceptualization on a domain, then the PED&I ontology eases the communication among the different actors involved in the design and the normative verification on pressure equipments. The terminology and the design details we formalize are trustworthy, because they have been formalized in strict collaboration with experts in this field. The PED&I ontology has been written in OWL (Web Ontology Language), which syntax and semantics have been formalized and are available to public. Then, the interaction of software modules with the tool we propose via the PED&I ontology is straightforward.

In the tool described in this article, once a pressure equipment model is represented in the PED&I ontology, its compliance with the VSR normative can be checked. This operation can be performed both during the design phase, thus assisting the designer, and, once the model is released, during safety inspections. In both cases, given the equipment model, the norms applicable to it are retrieved from the ontology, then geometric and functional constraints can be verified through the KBE module of the CAD system. The check is performed in a semi-automatic environment, that is, the system highlights the possible violations to the user, which decides on the required interventions.

The selection of the correct normative is obtained through the formalization of the logical constraints that relate each equipment to the corresponding set of safety rules. This is realized through the specification of the ontology classes that represent the conceptual entities of the domain (e.g., pressure equipments, safety rules) and the corresponding logical axioms, that must be verified by the entities of these classes; the relationships among these entities; and the logical rules, written in SWRL (Semantic Web Rule Language), that enable to infer new logical relationships among the class instances. In particular, the logic rules execution makes explicit whether a set of norms applies to a given equipment.

The ontology can be extended to support different equipments and rules related to the domain of pressure vessels and component. Furthermore, the methodology we apply for the KB tool design can be applied to any well formalized domain requiring the verification of rules and constraints.

The article is organized as follows. In Section 2 the research background and an overview of related works are illustrated. In Section 3 we introduce the general architecture of the KB system, whereas in Section 4 we discuss the design of the knowledge base of the system, i.e. the PED&I ontology. In Section 5 we introduce the developed prototype through an application example to illustrate how the defined ontology supports the certification of safety rules for pressure equipments. Finally, benefits and limitations of the approach are discussed in Section 6, which concludes the article.

BACKGROUND AND RELATED WORKS

The set of safety rules we represent in the tool knowledge base is the VSR code [2], developed in Italy in the early seventies by constructors and public bodies and enforced by the law for pressure vessels verification. The VSR code is analogous to other codes developed by main industrialized countries, such as BS5500 in UK, ASME VIII-div.1 in USA and AD-MERKBLATT in Germany. For 20 years,
I.S.P.E.S.L.\(^5\) has been in charge to manage and update the VSR code in Italy. In 1997, the European Commission issued the PED directive 97/23/CE to allow the free trade of pressure equipments across the European Union. The Directive does not enforce any national code, but defines only general criteria, named Essential Safety Requirements, which have to be verified to approve pressure equipments. VSR code has been harmonized with PED directive, and nowadays it is widely used in Italy for pressure equipments design and approval.

The development of computer-aided tools for enhancing plant safety has been recognized as an important issue and several researches address the various aspects of the problem. In Gabbar et al. [3] investigate limitations and issues in managing safety related activities throughout the plant lifecycle and propose a framework for computer-aided plant safety management systems.

To assess the compliance to safety conditions, in the recent past, the verification of process plants has been improved through the application of KB technologies. In two works [4,5], both originated from the research carried out in the European project HIDA [6], the authors apply KB technologies to the assessment of cracks in plant components, underlining the benefits deriving from the incorporation of defect checking code into a KB system. In the project TTF \(^2\), which is supported by the European Pressure Equipment Research Council and is aimed at promoting the use of High Strength Steels, the integration of a new analysis method with appropriate material data into a KB system is proposed. The system is intended to be used by both pressure vessel designers and standardization bodies, who are responsible for accepting new materials into design standards and for determining the material values.

More recently, KBE tools rely on ontologies, which are recognized as an effective technological support for the formalization of knowledge rich models including sophisticated logical relationships and constraints. An ontology is a “specification of a conceptualization” [7], i.e., a representation of the knowledge of a domain of interest, which is associated with a semantic network structure [8]. Ontology and other semantic web technologies differ from traditional DBMS because they provide effective reasoning capabilities: for instance, through the check of logical axioms and the application of reasoning rules, it is possible to infer new knowledge from data already stored.

Ontologies in engineering have been used mainly for sharing and reusing both domain and functional knowledge [9]. In [10], ontologies have been applied to the semantics-driven simplification of CAD models, aimed at the visualization and the design review of large plant models. In [11] an ontology-based tool for the support of the structural design process is presented.

Similarly to [3,5,6,10], in this article we provide a formalization of expert’s knowledge aiming at the verification of the safety of process plants. However, differently from those works, we propose a KB tool for the automatic check of pressure equipment safety rules encoded in ontologies. Moreover, differently from other KBE works which apply ontologies, we exploit their potentialities not only for the representation of the domain knowledge, rather we investigate the application of the reasoning capability they provide, through the specification of the relationships among classes and of axioms that check the belonging of instances to domain classes and their participation to relationships.

The research presented in this article relies and extends the work presented in [12]; herein the knowledge base have been expanded and effective reasoning capabilities have been added. The application of logical rules introduces a significant novelty in the methodology applied, because implicit knowledge can be inferred whenever a new instance is inserted in the ontology, improving the clearness of the formalization of the domain knowledge and enabling its complete representation.

**A KNOWLEDGE-BASED SYSTEM FOR PRESSURE EQUIPMENT SAFETY**

The KB environment we propose to support both the design and the certification of pressure equipments is illustrated in Figure 1.

The PED&I system GUI is the graphical user interface through which users access all the tool functionalities. Through this GUI, the PED&I Ontology can be queried easily and effectively, retrieving all the information needed on the pressure equipments and the related safety rules.

The KB-CAD/PDM is the computer-aided design system adopted to model the shape of the pressure equipments, which are stored in the CAD models repository. It can be integrated in a Product Data Management (PDM) system.

The PED&I ontology includes a taxonomy of pressure equipments, safety rules, (i.e., VSR/PED codes and their metadata), inference rules and logical axioms. The ontology relates safety rules to CAD data (models, features, and parameters) of pressure vessels and equipments.

The safety rule reasoner is the software module that interacts with the ontology to handle the design and the inspection of pressure vessels in compliance with the adopted normative. This is the module that executes the queries against the PED&I ontology, and executes the logical rules against the ontology instances.

When an equipment model is analyzed or when the designer creates new equipments or equipment components, their dimensions and operating conditions are automatically checked and the compliance with the adopted normative is verified. The safety rule reasoner queries the ontology and retrieves the corresponding rules, which are translated into KB statements in the language of the KB-CAD system in use, and then verified on the model under evaluation.

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\(^5\)I.S.P.E.S.L, Istituto Superiore per la Prevenzione e la Sicurezza del Lavoro. Web page: [http://www.ispesl.it/](http://www.ispesl.it/) (Accessed February 2008).

\(^6\)[http://www.eperc.bam.de/projects/ttf2.html](http://www.eperc.bam.de/projects/ttf2.html) (Accessed February 2008).
For the pressure vessel designer, rules correspond to a set of design directives to follow and dimensional parameter dependences to satisfy to obtain safe components. By contrast, from the inspection point of view, once the user has specified the data of the equipment to be certified, the system firstly rebuilds a synthetic digital representation of the equipment to provide a simplified but meaningful CAD model. Then, the translated safety rules can be automatically verified on the rebuilt digital representation.

THE PRESSURE EQUIPMENT DESIGN AND INSPECTION KNOWLEDGE BASE

In this section, we present the design of the PED&I ontology, which has been defined following a bottom-up approach, relying on the analysis of the VSR rules collection, and in collaboration with experts in the field, to guarantee the adequacy of the terminology and equipment parameterization. The ontology has been specified in OWL-DL, the description logic sublanguage of OWL. Inference rules have been defined in SWRL, the W3C’s proposal for a semantic rule web language.

The PED&I ontology represents the conceptual entities, with their relationships, involved in the domain of pressure equipments (e.g., vessel for fluids, vessel components and materials, safety rules). A simplified schema, reporting the main concepts, is shown in Figure 2. For the sake of readability, we report classes and relationships, disregarding class attributes.

In Figure 2 rectangles are ontology classes, which represent the domain concepts. The enclosed labels indicate the class names.7 Classes with labels in italic are abstract, i.e., no instances will be created for those classes; they are used to model common concepts. Unlabelled arrows with a thick tip represent the relationship is-a. For example, Junction is-a (specific type of) Component. is-a enables property inheritance among the classes involved, and through this relationship the ontology concepts are classified and organized in taxonomies. Moreover, relationships have a direction, and those with a starred label (rel*) have multiple target. For example, the relationship hascomponent, holding from Vessel for fluids to Component, enables to represent a vessel for fluids as composed of more than one element (e.g., its shell, two ends, several openings). Finally, relationships with underlined labels (rel) are mandatory. A Vessel for fluids, for example, is made of at least one vessel Component.

In the following, first we focus on the formalization of the safety rules through illustrative examples, then we give an overview of the axioms which ensure ontology consistency.

Safety Rules

The code VSR/PED [2] represents the core of the PED&I ontology. The VSR code is organized in chapters, according to the different pressure equipments. It rules the whole pressure equipment lifecycle, including rules for construction, testing, inspection along operation time, repair and modification. Moreover, VSR/PED defines the operative technical specifications for the verification of the stability of pressure vessels, giving the safety conditions on pressure vessels and components (e.g., shells, ends, plates), equipments, and every model detail (e.g., stiffening rings, openings), like, for instance, the minimal thickness of vessel components. Safety conditions are
expressed as functions of geometrical parameters (e.g., diameter, length, volume), operational parameters (e.g., peak pressure, operation temperature) and material features (e.g., elasticity modulus, corrosion allowance). In the following example, we describe a VSR rule.

**Example 1**

Given the VSR code, the set of rules VSR.1.N applies to the stability check of heat exchanger (HE) tube sheets made by unalloyed steel or weakly alloyed steel (austenic steel excluded). In particular, the rule VSR.1.N.6.3 applies to the check of welds of heat recovery steam generator tube sheets (HRSG), a specific type of HEs. According to the type of junctions between the tube sheet and its shell, several tests have to be applied. For instance, point 3 of the rule VSR.1.N.6.3 (see Figure 3) specifies the weld tests to carry out for tube sheets with type C junctions.

In the ontology, we define the class VSR/PED rule to represent every rule of the VSR/PED code (cf. Figure 2). VSR/PED rule is a sub-class of Safety rule, whose individuals represent the criteria for the plant safety assessment. Each safety rule has a unique name (e.g., VSR.1.N.6.3), and a textual description (i.e., the text that describes the rule) that can be visualized by the experts at their convenience. The description can include also some illustrations to help the rule interpretation and application.

A safety rule modeled by an instance of Safety rule applies to one or more components of a vessel for fluids, which is designed to contain a particular substance. A component is made of a given material among those employed in the vessel construction. The same rule may apply to different substances...
among those the vessel has been designed to contain, and to the (set of) material(s) employed for the manufacturing of the vessel and its components.

A rule can be subdivided into sub-rules, which may be complementary, or in alternative to a different set of rules. Each rule may specify one or more constraints, either geometrical, operational, or functional. Analogously to rules, a constraint may be complementary or in alternative to other constraints. A geometric and functional constraint is usually specified as a computation that involves a set of parameters. A parameter may be geometric (e.g., length, area, distance, thickness, etc.) or functional (e.g., pressure, temperature, etc.). Often a parameter is defined as a function of other parameters.

The check of a safety rule or constraint is performed according to safety tests, which are executed on the equipment the rule applies to. To link the rules’ checks to the CAD models, geometric constraints and parameter extraction procedures are linked to the corresponding procedures of the specific KB-CAD system in use. Following these domain requirements, in the following example we illustrate how the safety rules of Example 1 have been modeled in the ontology. Instance names in the ontology recall the real rules names, being a key code for people familiar with the VSR norms.

**Example 2**

To model point 3 of rule VSR.1.N.6.3 we create the individual [VSR.1.N.6.3-1] of type VSR.1.N.6.3 (see Figure 4). This instance will be associated to the individuals representing the specific equipment, material, vessel and substance the rule VSR.1.N.6.3 applies to through the relationships appliesTo/basRule, in particular, enables to retrieve the safety rules that apply to a given vessel and to its components.

Point 3 of rule VSR.1.N.6.3 requires the application of safety rules defined in another collection, i.e., collection S. Then, the instance [VSR.1.N.6.3-1] refers, through the relationship AND, to the instances of this set of rules, which are modeled in the ontology as individuals of class S rule, a sub-class of Safety rule. Point 3 of rule VSR.1.N.6.3 is composed of three constraints, as illustrated in (see Figure 3). Through the relationship hasConstraint, [VSR.1.N.6.3-1] refers to three instances of type Constraint, namely [VSR.1.N.6.3-ctr1], [VSR.1.N.6.3-ctr2], and [VSR.1.N.6.3-ctr3]. [VSR.1.N.6.3-ctr1] models the first paragraph of this point (cf. Figure 3, rectangle c1). This is an engineering constraint, because it specifies engineering conditions on how to realize welds.

[VSR.1.N.6.3-ctr2] is a geometric constraint, because it specifies the relationships among geometric quantities, i.e., the distance c and the outside diameter d of each tube that composes the tube sheet, for the specific junctions. The constraint is given by the formula: c ≥ 1.5d, which is stored as the value of

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9I.S.P.E.S.L. (Istituto Superiore per la Prevenzione e la Sicurezza del Lavoro) (1999), Raccolta S, Specificazioni tecniche applicative del DM 21.11.1972 riguardanti l’impiego delle saldature nella costruzione e riparazione degli apparecchi a pressione. Roma - Istituto Poligrafico e Zecca dello Stato - Libreria dello Stato.
the attribute `hasFormula` of [VSR.1_N.6.3-3-ctr2]. `c` and `d` are represented by the individuals [distance between tube sheets] and [outside diameter], respectively, which are geometric parameters related to [VSR.1_N.6.3-3-ctr2] through the relationship `hasParameter`. The constraint is translated in a specification interpretable by the KB module of the CAD system, which will be used to check the rule. An individual of type CAD statement, i.e., [VSR.1_N.6.3-3-ctr2-cad], represents the specification for this constraint. The two individuals are related through the relationship `hasKBCADStatement`.

The last constraint of the rule is represented by the individual [VSR.1_N.6.3-3-ctr3], of type engineering project condition. The parameters and the formula are modeled as described above for the individual [VSR.1_N.6.3-3-ctr2].

### Ontology Axioms and Restrictions

The consistency of the PED&I ontology is ensured through the check of class axioms, which formalize restrictions on property values, i.e., they bind the instance properties to consistent values, according to their semantics. For instance, specific restrictions bound the codomain of the relationship **`appliesTo`** to the sub-classes of `Pressure Equipment`, specializing the rule application to the correct component type.

The axioms are specified as description logic formulas, according to the syntax of OWL-DL. The expressiveness of OWL-DL is limited by decidability and performance requirements, allowing to represent very simple constraints. Nonetheless, the set of constraints we specified, combined with the logical rules we describe in the following section, allows an adequate support to the user in the safety rules verification during both the inspection and the design phases.

### Reasoning Rules

Starting from the information already formalized in the ontology and from the data the user inserts, the execution of SWRL rules enables to infer implicit knowledge. For instance, whenever the reasoner\(^\text{10}\) executes the following rules against the tool knowledge base

\[
\begin{align*}
\text{Pressure Vessel}(?x) \land \text{VSR/PED Rule}(?y) \\
\rightarrow \text{appliesTo}(?y, ?x), \\
\text{Pressure Equipment}(?x) \land \text{VSR/PED Rule}(?y) \\
\rightarrow \text{appliesTo}(?y, ?x),
\end{align*}
\]

\(^{10}\)We apply the RacerPro OWL reasoner, by Racer Systems GmbH & Co. Web site: [http://www.racer-systems.com/index.phtml](http://www.racer-systems.com/index.phtml) (Accessed February 2008).

every instance in the ontology representing a VSR/PED safety rule is linked to any existing individual of type `Pressure Vessel` and `Pressure Equipment` via the relationship `appliesTo`. Note that the reasoner sets the correct value also for the inverse relationships (`basRule` in the previous example).

Differently from the axioms, which allow to perform \textit{a-posteriori} consistency checks of the instances in the ontology, the execution of a rule sets automatically the implicit relations that satisfy the rule conditions and that have not been explicitly specified by the user. In the previous example, the association between the pressure vessel component under design and the applicable rules is performed.

In the following example we describe some of the logical rules involved by the safety rule of Example 1.

#### Example 3

The relationship values that will be set via SWRL rules for the safety rules of chapter VSR.1.N have been represented in (see Figure 5). For instance, the execution of the rules:

\[
\begin{align*}
\text{Tube Sheet}(?x) \land \text{Weakly Alloyed Steel}(?y) \\
\land \text{isMadeOf}(?x, ?y) \land \text{VSR.1.N}(?z) \\
\rightarrow \text{appliesTo}(?z, ?x) \\
\text{Tube Sheet}(?x) \land \text{Unalloyed Steel}(?y) \\
\land \text{isMadeOf}(?x, ?y) \land \text{VSR.1.N}(?z) \\
\rightarrow \text{appliesTo}(?z, ?x),
\end{align*}
\]

sets consistently the relationships `appliesTo/basRule` for the rules of chapter VSR.1.N to tube sheet made by weakly alloyed and unalloyed steel. The same happens for each equipment considered by the VSR code. In particular, the SWRL rules of interest for the safety rule VSR.1.6.3 are:

\[
\begin{align*}
\text{HRSG Tube Sheet Type C}(?x) \\
\land \text{Weakly Alloyed Steel}(?y) \land \text{isMadeOf}(?x, ?y) \\
\land \text{VSR.1.N.6.3-3}(?z) \rightarrow \text{appliesTo}(?z, ?x) \\
\text{HRSG Tube Sheet Type C}(?x) \land \text{Unalloyed Steel}(?y) \\
\land \text{isMadeOf}(?x, ?y) \land \text{VSR.1.N.6.3-3}(?z) \\
\rightarrow \text{appliesTo}(?z, ?x).
\end{align*}
\]

Whenever these rules are executed, they set the values for the relationships `appliesTo` and `basRule` among HRSG tube sheets of type C and the above mentioned safety rule.

Several rules are required to set the values for \textit{AND} and \textit{XOR} relationships for VSR.1.N.6 individuals. For instance, safety rules VSR.1.N.6.1, VSR.1.N.6.2, VSR.1.N.6.3 are complementary.

### The PED&I Tool Prototype

To prove the validity of the proposed KB environment, a software prototype has been developed based on CATIA V5\(^{11}\) customization tools for accessing geometric data, and on the CATIA V5

\(^{11}\)Dassault-Systèmes. Web site: [http://www.3ds.com/products-solutions/plm-solutions/catia/](http://www.3ds.com/products-solutions/plm-solutions/catia/) (Accessed February 2008).
knowledgeware module for defining the CAD statements expressing the design rules retrieved from the knowledge base.

The PED&I system GUI [13] is easy to employ and close to the usual way of working both of designers and inspectors. In fact, pressure vessel designers are used to fill in detailed forms to obtain the required VSR compliance certificate, and the PED&I system GUI follows the same approach. Therefore, designers do not need to learn a new specific and complex tool.

At the design stage, the user describes the general type of apparatus he/she is designing, specifying its dimensions and operating conditions (e.g., pressure, temperature, materials, type of fluids, and main features), by selecting it from an electronic catalogue. Then, he/she adds the various elements, e.g., ends and shells, and defines the related parameters according to the VSR notation. Details, such as branches openings or nips, may be added on the main items (shell or ends); they are defined by specifying their parameters through a VSR-like interface and are positioned using CATIA V5 commands.

According to these specifications, the corresponding instances in the ontology are created and automatically linked to the concerned rules. In this way, following a guided path, the designer creates the solid model of the part, which is the essential input for the containment verification as well as for the stress calculations.

From the inspection point of view, currently we adopted the procedure of letting the user to rebuild a synthetic digital representation of the equipment, in a manual but assisted way, using just the data supplied by the manufacturer in the certification request form. A synthetic equipment model is created in the CAD system, and then the VSR rules, retrieved through the ontology, can be automatically checked.

As an example, let us suppose an inspector is going to verify the safety compliance of the model of a HRSG tube sheet. In the ontology the creation of the HRSG Tube Sheet Type C individual [HRSGTubeSheetTypeC-1] is required to represent this vessel component. As the tube sheet is made of weakly alloyed steel, then [HRSGTubeSheetTypeC-1] is related to a Weakly alloyed steel individual through the relationship isMadeOf. The OWL reasoner retrieves the correct Safety rule individuals relying on the logical axioms and rules we defined for tube sheets and the related safety norms. In particular, after the execution of the SWRL rules described in Section 4.3, the HRSG Tube Sheet Type C individual [HRSGTubeSheetTypeC-1] is correctly related to the safety norms of interest, i.e., the most specific rule VSR.1.N.6.3.3 and the more general rules VSR.1.N.6, VSR.1.N, and VSR.1.

Once the values of the instance relationships are correctly filled in, the ontology can be queried to provide the information the inspector is interested in about this particular tube sheet, i.e., the safety rules and the related geometric constraints for the given pressure equipment.

All the rules applicable to the equipment under consideration are visualized by the graphical user interface.
interface with a traffic light icon associated, as normal practice in CATIA V5: a green light means compliance, whereas a red one means discrepancy, as illustrated in (see Figure 6).

**DISCUSSION AND CONCLUSIONS**

The research work presented in this article exploits the potentialities offered by KB technologies to the design and certification of pressure equipments. In particular, the article focuses on the definition of a knowledge base, composed of an ontology, a set of logical axioms and logical rules, designed to support both the application of a specific safety normative in the first stages of the pressure vessels design process, and its verification *a posteriori* by inspection bodies.

The present version is restricted to the VSR normative, as applied in Italy. However, the use of ontologies to model the application domain enables a straightforward extension to a wider domain and to other safety rules than VSRs. In particular, given the ontology described in Section 3, the complete domain of vessel for fluids can be easily managed. The extension of the ontology is straightforward. First, the new classes representing the sets of rules and their application domain have to be defined as sub-classes of the classes in the ontology, specifically those that represent the overall concepts, e.g., Safety rule, Component. Then, the instances of these new classes must be inserted, setting correctly the relationships among them, and the related axioms and rules must be specified.

As for the domain knowledge, another advantage of the described architecture is that other KB-CAD systems than CATIA V5 can be supported, simply by extending the ontology with the opportune classes and instances and changing the CAD statements according to the system under consideration.

In contrast, the main limitation of the proposed approach is inherent to the need of using the specific features and parameters (i.e., those included in the ontology specification) for describing the vessel model to automatically verify the involved norms. This could not be guaranteed because the same object can be designed differently depending also on the specific CAD system capabilities. Anyhow, vessels are described in the ontology in terms of features and parameters, which are meaningful from the functional point of view and therefore really close to the designer. However, the fully automatic verification of the safety rules compliance on an already defined CAD model from the inspector point of view would require the use of an automatic or interactive feature recognition system, which has not been fully tested to verify its effectiveness. This would require some additional effort to put the extracted parameters in relation with those considered in the ontology.

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