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Ontology driven certification of pressure equipments

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Abstract

Standards and engineering codes rule design, construction and operation of chemical plant equipments to ensure reliability and safety. In this paper, 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 CAD 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 paper 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.

Keywords: Safety rules compliance; risk analysis; pressure equipments; ontology; knowledge management; knowledge-based CAD.

1. 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 in order 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

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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 practise 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, in order 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) allows 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 paper is the definition of a knowledge-based (KB) design

¹ COMAH Safety Report assessment manual – Level III Technical aspects. Web page: <http://www.hse.gov.uk/comah/sragtech> (accessed February, 2008).

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 & 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/EC², 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 Language³), 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 paper, 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

² Pressure Equipment Directive (PED) 97/23/EC, 1997. Web page: http://europa.eu.int/comm/enterprise/pressure_equipment/ped/index_en.html (accessed February 2008).

³ OWL, Web Ontology Language Reference. W3C Recommendation 10 February 2004. World Wide Web Consortium. Web site: <http://www.w3.org/TR/owl-ref/> (accessed February, 2008)

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 Language⁴), 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 paper 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, while 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 paper.

2. 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 twenty 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/ in order 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.

⁴SWRL: A Semantic Web Rule Language, Combining OWL and RuleML. W3C Member Submission 21 May 2004. web site: <http://www.w3.org/Submission/SWRL/> (accessed February, 2008)

⁵ I.S.P.E.S.L., Istituto Superiore per la Prevenzione e la Sicurezza del Lavoro. Web page: <http://www.ispesl.it/> (accessed February, 2008).

The development of computer-aided tools for enhancing plant safety has been recognised as an important issue and several researches address the various aspects of the problem. In [3] Gabbar et al. 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 2⁶, 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 standardisation 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 paper 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

⁶ <http://www.eperc.bam.de/projects/ttf2.html> (accessed February, 2008)

other KBE works which apply ontologies, we exploit their potentialities non 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 paper 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.

3. 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.

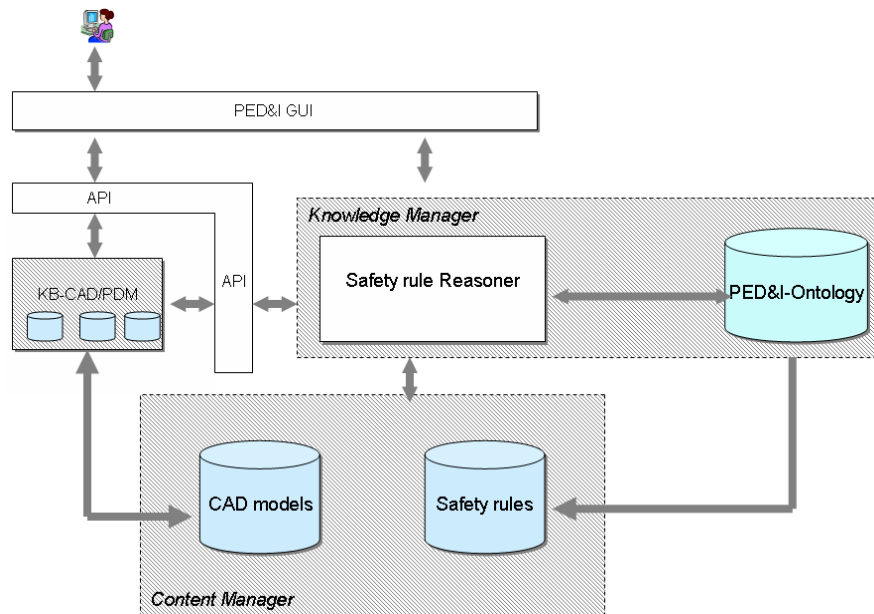


Figure 1. KB system for Pressure Vessel design and inspection.

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 analysed 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 KBE statements in the language of the KB-CAD system in use, and then verified on the model under evaluation.

For the pressure vessel designer, rules correspond to a set of design directives to follow and dimensional parameter dependences to satisfy in order 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.

4. The Pressure Equipment Design & 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 parameterisation. 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 names⁷. 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*.

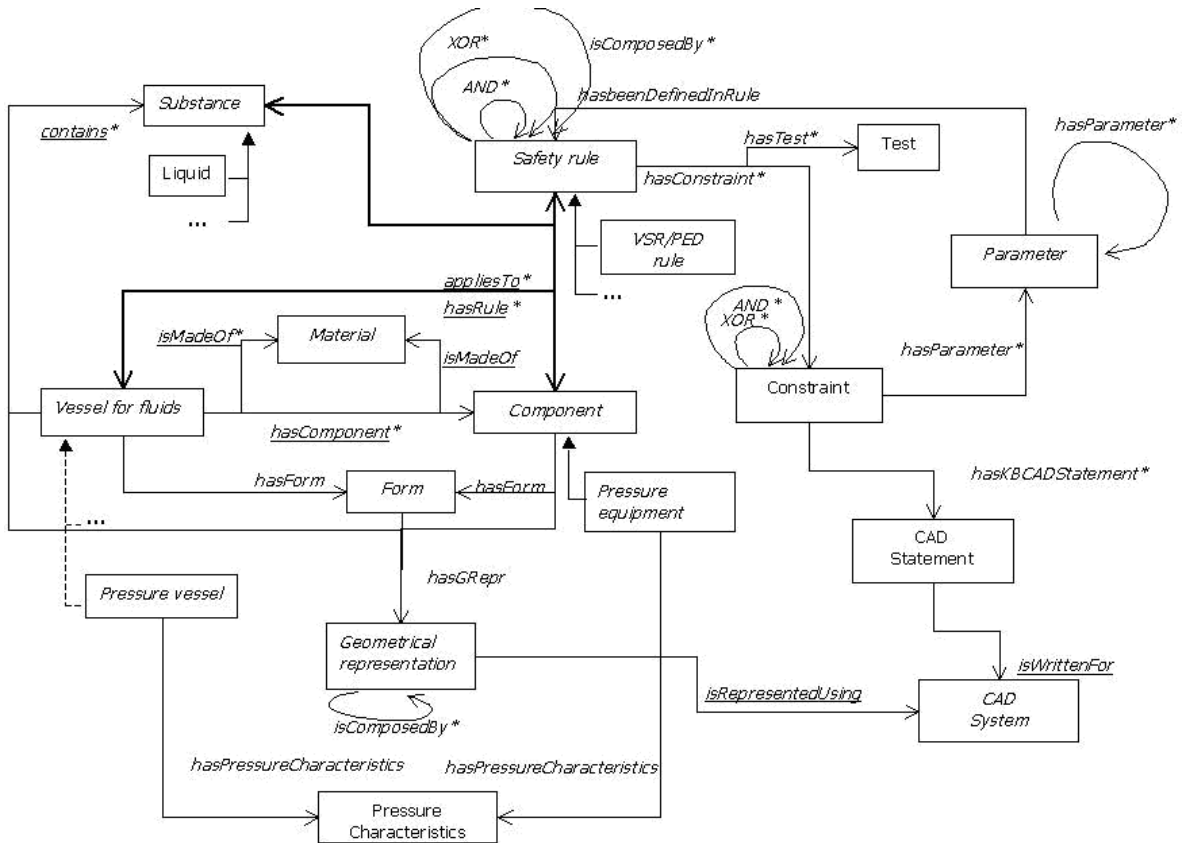


Figure 2. A simplified schema of the main domain concepts and their relationships.

In the following, first we focus on the formalization of the safety rules through illustrative examples, then we

⁷ For the sake of comprehension, composite class names are strings without spaces. Note that spaces are omitted, or substituted by underscores () in the OWL file, where a class name is a string without spaces.

give an overview of the axioms which ensure ontology consistency.

4.1 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 (austenitic 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 heat exchangers. 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 (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 visualised by the experts at their convenience. The description can include also some illustrations to help the rule interpretation and application.

A safety rule modelled 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.

VSR 1.N.6.3.3 - C Type Tube sheet

c1. The preparation of the edges and the dimensions of the fillet welds that connect the tube sheet with the shell shall comply with the S Collection rules; anyway such a weld shall be a full penetration weld; on it, after each pass, either a magnetic particle test or a dye penetrant test has to be carried out.

The distance c , in mm, between the axis of the outer tube and the inside diameter of the shell shall comply with both the following formulas:

c2. $c \geq 1,5d$

c3. $c \geq 3,48 \sqrt{\frac{s \cdot L}{f}}$

where:

d outside diameter of the tube, in mm;
 L distance between the tube sheets, in mm;
 s thickness of the tube sheet, in mm;
 f maximum allowable stress of the tube sheet material at the design conditions, in MPa.

Figure 3. Point 3 of the rule VSR.1.N.6.3.

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 modelled 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_3-1]* of type *VSR_1_N_6_3_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/hasRule*⁸. *hasRule*, in particular, enables to retrieve the safety rules that apply to a given vessel and

⁸ The values of such relationship are set and bounded according to logical rules and class axioms we will discuss in the following Sections.

Point 3 of rule VSR.1.N.6.3.3 requires the application of safety rules defined in another collection, i.e., collection S⁹. Then, the instance *[VSR_1_N_6_3_3-1]* refers, through the relationship *AND*, to the instances of this set of rules, which are modelled in the ontology as individuals of class *S rule*, a sub-class of *Safety rule*. Point 3 of rule VSR.1.N.6.3.3 is composed of three constraints, as illustrated in (Figure 3). Through the relationship *hasConstraint*, *[VSR_1_N_6_3_3-1]* refers to three instances of type *Constraint*, namely *[VSR_1_N_6_3_3-ctr1]*, *[VSR_1_N_6_3_3-ctr2]*, and *[VSR_1_N_6_3_3-ctr3]*. *[VSR_1_N_6_3_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.

[illegible]

⁹ I.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.

execution of SWRL rules enables to infer implicit knowledge. For instance, whenever the reasoner¹⁰ executes the following rules against the tool knowledge base

$$Pressure\ Vessel(?x) \wedge VSR/PED\ Rule(?y) \rightarrow appliesTo(?y, ?x),$$

$$Pressure\ Equipment(?x) \wedge VSR/PED\ Rule(?y) \rightarrow appliesTo(?y, ?x),$$

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 (*hasRule* in the previous example).

Differently from the axioms, which allow to perform *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 (Figure 5). For instance, the execution of the rules:

$$Tube\ Sheet(?x) \wedge Weakly\ Alloyed\ Steel(?y) \wedge isMadeOf(?x, ?y) \wedge VSR_1_N(?z) \rightarrow appliesTo(?z, ?x)$$

$$Tube\ Sheet(?x) \wedge Unalloyed\ Steel(?y) \wedge isMadeOf(?x, ?y) \wedge VSR_1_N(?z) \rightarrow appliesTo(?z, ?x)$$

sets consistently the relationships *appliesTo/hasRule* 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.1.6.3.3 are:

$$HRSG\ Tube\ Sheet\ Type\ C(?x) \wedge Weakly\ Alloyed\ Steel(?y) \wedge isMadeOf(?x, ?y) \wedge VSR_1_N_6_3_3(?z) \rightarrow appliesTo(?z, ?x)$$

$$HRSG\ Tube\ Sheet\ Type\ C(?x) \wedge Unalloyed\ Steel(?y) \wedge isMadeOf(?x, ?y) \wedge VSR_1_N_6_3_3(?z) \rightarrow appliesTo(?z, ?x).$$

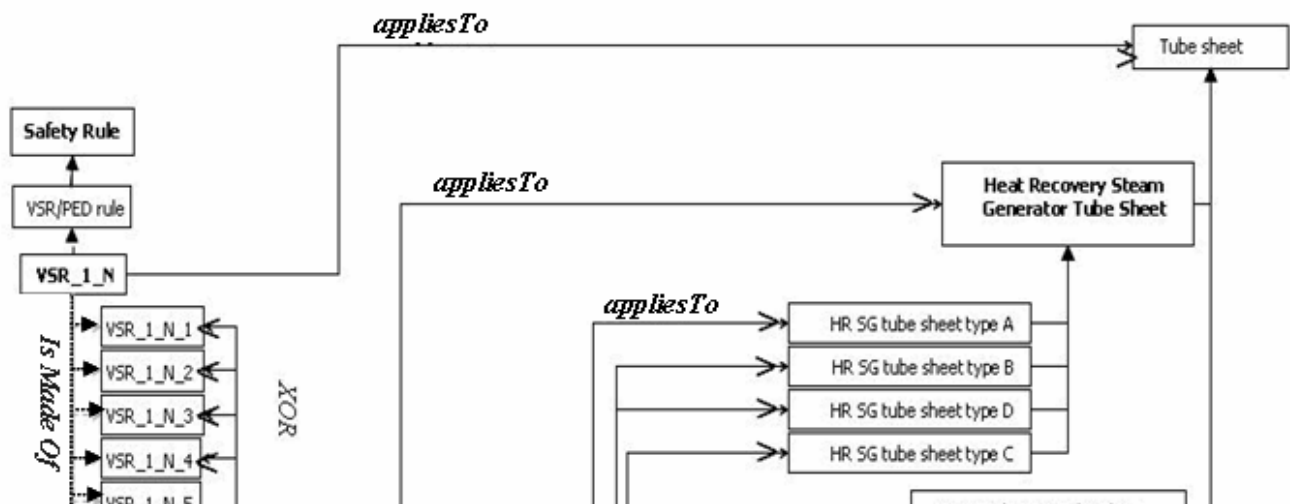


Figure 5. Relationship values for safety rule VSR.1.N.6.3.3 set via SWRL rules.

Whenever these rules are executed, they set the values for the relationships *appliesTo* and *hasRule* among heat recovery steam generator tube sheets of type C and the above mentioned safety rule.

Several rules are required to set the values for *AND* and *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. ♦

5. 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} customisation tools for accessing geometric data, and on the CATIA_V5[®] *knowledgware* 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

¹¹ Dassault-Systèmes. Web site: <http://www.3ds.com/products-solutions/plm-solutions/catia/> (accessed February 2008)

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.I.N.6.3.3* and the more general rules *VSR.I.N.6*, *VSR.I.N* and *VSR.I*.

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 the pressure equipment.

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

6. Discussion and Conclusions

The research work presented in this paper exploits the potentialities offered by KB technologies to the design and certification of pressure equipments. In particular, the paper 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.

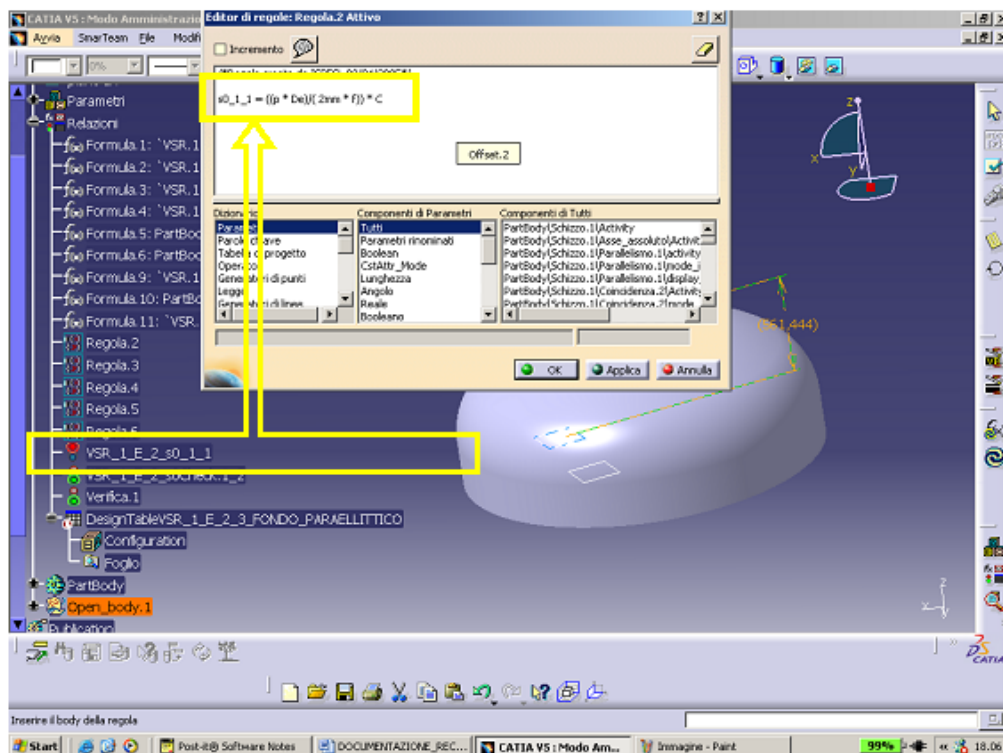


Figure 6. PVD&I tool for inspector: in this example, as the thickness of this quasi-elliptical end does not comply with

the formula 1.1 in VSR.1.E.2 rule, the “red light” indicates that a deviation occurs.

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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