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# ON-SMMILE: Ontology Network-based Student Model for MultIple Learning Environments

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ABSTRACT

Currently, many educational researchers focus on the extraction of information about the learning progress to properly assist students. We present ON-SMMILE, a student-centered and flexible student model which is represented as an ontology network combining information related to (i) students and their knowledge state, (ii) assessments that rely on rubrics and different types of objectives, (iii) units of learning and (iv) information resources previously employed as support for the student model in intelligent virtual environment for training/instruction and here extended. The aim of this work is to design and build methodologically, throughout ontological engineering, the ON-SMMILE model to be used as support of future works closely linked to supervision of student's learning as competence-based recommender system. For this purpose, our model is designed as a set of ontological resources that have been extended, standardized, interrelated and adapted to be used in multiple learning environments. In this paper, we also analyze the available approaches based on instructional design which can be added to ontology network to build the proposed model. As a case study, a chemical experiment in a virtual environment and its instantiation are described in terms of ON-SMMILE.

## 1. Introduction

The latest advances in AI have motivated a renewed interest in educational research. One of the main goals of this discipline is to support instructors in their teaching process by providing them with information associated to the state of the student knowledge. Educators usually employ techniques and tools of learning analytics to monitor and diagnose such information with the purpose of providing students a personalized learning. Siemens [1] defines learning analytics as "the use of intelligent data, learner-produced data, and analysis models to discover information and social connections, and to predict and advice on learning". The monitoring process applied to the educational field is defined as the activity of tracking student progress along the instruction sequence [2]. In this context, the goal of diagnosis process is to infer, essentially from the students' behavior, which learning objectives have been achieved by the student and the state of their knowledge. This kind of diagnosis is called pedagogic diagnosis when it is expressed in terms of acquired learning objectives and cognitive diagnosis, when it is expressed in terms of knowledge objects.[1] Thus, thanks to the conclusions reached by the diagnosis process, it is possible to properly guide the student across his/her learning process [3]. These terms, learning analytics, monitoring and diagnose are closely related because they focus on same purpose, i.e., contribute

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[1] It should be noted that pedagogic diagnosis is included into cognitive diagnosis.

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to the improvement of the teaching/learning process. Accordingly, we take them into account in this research. Although learning analytics tools are commonly used, there are no flexible monitoring or diagnosis approaches that can be applied to (i) a wide variety of course delivery modes (e.g. fully face-to-face, web-enhanced, flipped, blended, fully on-line), (ii) learning/instructional strategies such as setting objectives and providing feedback, generating and testing hypothesis or cooperative learning, (iii) types of learning experiences, for example, problem solving. In contrast, educators use different instruments and tools available in specific environments, such as Learning Management Systems (LMS) or Virtual Environments (VE), to partially supervise learning progress of students.

Our motivation is to offer the instructors a flexible student model that provides different indicators such as: (i) properties about students and their knowledge, (ii) characteristics from activities and (iii) features from objectives. The instructors will be capable of detecting problems early through these indicators and thus, enhance the knowledge acquisition process. This student model will provide the necessary support for obtaining, analyzing and classifying extensive and meaningful information about students and their knowledge state. The modeling can even diagnose possible learning weaknesses and mistakes detected. These activities can help tutors with their decision-making tasks about what recommendations should be raised to each student. The instructors usually employ different platforms, methodologies or strategies to collect data about students to classify and analyze it. For example, in a biology module, dangerous laboratory practices could be performed in a virtual environment, the assessment activities could be carried out in a LMS platform and theory classes fully face-to-face. This work can be applied to a wide range of educational experiences as the previous one and many others offered in several environments. Therefore, we consider that a suitable organization of learners knowledge and their learning process through a rigorous student model is an interesting starting point as it provides instructors with data regarding the educational process to improve the learning strategy in an adaptive (personalized) approach.

The aim of this work concerns the implementation of a modular ontology network involving the application of ontological reengineering and the use of non-ontological and ontological resources (both existing ones and created from scratch). This involves to carry out activities as ontology extensions, restructuring, merging etc., to represent the above-mentioned student model. Gruber [4] defines an ontology as a formal explicit specification of a shared conceptualization. The choice of using an ontology is motivated by the fact that it is a representation formalism which facilitates the expression of abstract concepts and properties easily reusable and extensible in different learning environments. Furthermore, it provides the ability to infer knowledge about the information represented in the ontology. In ontology engineering, concepts are intended to be explicitly described [5]. After building the ontology network, an evaluation process including validation and verification needs to be applied to detect and correct anomalies, pitfalls, inconsistencies, modeling mistakes, etc.

In this paper we present an Ontology Network-based Student Model for MultI Learning Environment (ON-SMMILE) responsible for the structuring and representation of a student model. This proposal is based on a constructivist learning model, in which students have a greater participation in their learning process as mainly suggested by Piaget [6]. It will group ontologies related to the learning process to serve as a support model of an adaptive tutoring (human/software).

Our proposal combines the Student Model ontology network (SM) with student independent ontologies such as the Assessment Rubric (AR), the Performance Indicator (PI) and the IMS Learning Design (IMS LD) ontologies to build an ontology network that will serve as the foundation to develop a competence-based recommender system in the future. The main element of this network is the SM, a flexible model applicable to different environments and domains. Concretely it was previously integrated in MAEVIF, a software platform for the development of Intelligent Virtual Environment for Training/Instruction (IVETs). The proposal followed a methodological guide to modeling adaptation which consists of four phases: (a) ontology adaptation, (b) diagnosis method adaptation, (c) ontology initialization and (d) evaluation [7]. Following this methodological guide, we achieve the specific objectives that correspond to the main contributions of this paper: (i) standardize the previously developed SM ontology; (ii) enrich the «LearningObjective» [2] ontology, belonging to SM ontology, with several taxonomies of skills to create a more comprehensive model which allow us to monitor a wider range of specific objectives (it, consequently, facilitates the diagnosis task to the instructors); (iii) create a new ontology network by interrelating the four previously described ontologies; (iv) include into the existent diagnosis method a set of SWRL rules related to the student's performance.

The rest of this paper is organized as follows. Section 2 reviews the related literature on education ontologies, student modeling, EMLs and taxonomies of objectives. Section 3 presents the resources employed in this work including ontological and non-ontological resources. The latter include taxonomies and standards. It also explains the ontology network building and evaluation. In Section 4, the ON-SMMILE modeling is presented using a real case study which takes into account new properties, ontologies and classes. Finally, we discuss the results before we draw conclusions and present the future lines of work in Section 6.

## 2. Related work and background

As previously mentioned, this paper presents ON-SMMILE, an ontology network which organizes the information obtained from the student model in accordance with standard specifications. The main aim is that the information stored in terms of this ontological network will constitute a rich source of information for instructors. It will provide an adaptable and flexible just-in-time tutoring according to the state of stored knowledge about each particular student in a wide variety of learning environments and domains.

Following the NeOn methodological guide [8], we searched ontological and non-ontological resources which provide coverage to the terminology from requirement analysis phase in the building of the ontology network. For this reason, we addressed an analysis

[2] So that the reader can clearly differentiate ON-SMMILE ontological terms from the rest of the paper, these are specified between the symbols «and».

of the related work regarding the most recent education-related ontologies, student models, the most important EML specifications and taxonomies of objectives. From this analysis, we intend to achieve a standard-compliant ontological network and to enrich the SM ontology as part of the development of ON-SMMILE.

### 2.1. Ontologies in educational field

Currently, one of the most popular educational ontologies is OMNIBUS. This ontology was developed by Mizoguchi et al. [9,10]. The authors proposed an ontological engineering solution to organize learning theories and build a theory-aware authoring system. This ontology is categorized into six basic concepts (*common world, learning world, instructional world, instructional design/instructional system design world, world of cognition and theory and model*) that represent the upper level IS-A structure of OMNIBUS. This proposal evolved from Psyché et al. [11] work which intended to achieve a standard compliant ontology based on EML and IMS LD standards. In addition to OMNIBUS, we highlight the *Semantic Web* works mainly addressed to e-learning education such as those explained in a recent literature review by Al-Yahya et al. [12].

However, other authors focus on the students; currently, it should be noted that within these works the SM ontology network is composed of seven ontologies describing the student and his/her knowledge state (see Section 3.1.1). The same approach was followed by Ameen [13] while developing the *Ontological Student Profile*, that organizes the information in academic, general and personal to be used in personalization systems. Vesin et al. [14] developed Protus 2.0, a tutoring system based on semantic web technologies that considers the learning style and the performance for course personalization. Korchi et al. [15] created an ontology network composed of the *Learner*, *Learner-Profile*, *Pedagogical-Activity* and *Pedagogical-Assistance* ontologies to facilitate the adaptation and individualization of learning. Closely related to the previous work, a patient model that groups the information in activity profile, personal profile and health profile was originated in 2015 [16]. Miranda et al. [17] proposed an ontology-based model for professional competence management within the SIRET project. This model aims to support the development of activities by inferring the person closer to requirements according to their competences. Paquette et al. [18] implemented an ontology-based competency model in the TELOS system to support personalization in MOOC (Massive Open On-line Courses). In this proposal, competences can be classified into ten different skills and four different performance levels. Concerning the educational settings, Rius et al. [19] recently developed an ontology-driven framework to specify, adapt and implement educational scenarios and activities. This framework follows a three-layer ontological architecture. The first layer describes patterns of educational settings, the second layer is responsible for adapting them to different institutions and the third layer is used to rewrite the patterns in accordance with different implementation prototypes.

Nowadays some specifications for learning analytics interoperability such as xAPI[3] or IMS Caliper[4] have been transformed into ontologies. These specifications enable learning environments to capture data from student interactions and to share it with other environments and users. However, they are currently not ready to diagnose or recommend elements. Many authors have also paid attention to other educational resources, e.g., rubrics [20], context modeling [21], feedback [22], etc. Hence, it is possible to obtain data from the most of the specific aspects related to education.

With respect to the described ontologies, we have decided to choose the SM ontology network as the main resource of our work because of the following reasons. First, it is student-centered and contains many properties related to the student's actions, traces, personality, etc. Second, it was designed to support different kinds of learning experiences (from traditional face to face activities to virtual environments sessions). Third, it has been successfully applied to student modeling supporting of non-monotonic diagnoses[5] to, among others, IVETs. Finally, it includes information regarding immersive environments, in which, students are represented as avatars capable of interacting with the elements of the environment through real elements (e.g. virtual reality glasses or gloves).

### 2.2. Student modeling

The student modeling presented here has been developed to be applied to different domains and environments, specifically to IVETs that include Intelligent Tutoring Systems (ITSs). Most of the authors consider that the Student Model is the core of ITS as it enables tutors the application of learning analytics or monitoring techniques to track the student performance [23]. According to Greer and McCalla [24], a comprehensive student model should include all the learner's prior relevant learning, his or her learning progress, the student's preferred learning style, as well as other types of learner-related information. In this section, we pay particular attention to the standards that model the learner information profile because many information concerning the student is registered in it. The student profile models should maximize reusability and portability to be adaptable to multiple environments. There are multiple learner profile models such as the proposed by Dolog [25] or FOAF [26]. However, among the most prominent proposals of student profile, we highlight the *Learner Information Profile (IMS LIP)* [27] and the *public and Private Information (PAPI)* [28].

*IMS LIP* is divided into eleven main categories required to support learning information: (1) *Identification* contains the general data for an individual or organization such as name, address and demographics; (2) *Accessibility* includes the cognitive, technical and physical preferences for the student and his/her capabilities, disability and eligibilities; (3) *Goal* encompasses the description of the personal objectives and aspirations; (4) *Qlc* involves information about qualifications, certifications and licenses awarded to

[3] https://experienceapi.com/.

[4] https://www.imsglobal.org/activity/caliper.

[5] non-monotonic diagnosis refers to the process of detecting and solving the contradictions that can arise in the process. For example, a student can learn a new knowledge or forget a previously acquired one.

**Table 1**
Characteristics of reviewed *EMLs*.

| EML | Learning app. | Structure | Personalization | Context |
|---|---|---|---|---|
| PALO [29] | Framework | 5 layers of categories | Entities and relationships | Prerequisites and organization |
| EML [30] | Specification | XML schema | Learner real needs | Objects and services |
| IMS LD [31] | Ontology | Activity-centered approach | 3 levels of design | Performance in the act |
| Ldl [32] | Metamodel | Teacher-centered approach | Pre-and post-conditions | Place, services and contents |
| poEML [33] | Language | Scenario-centered approach | Background information | 13 perspectives based on UOL |
| ISiS [34] | Graphical environment | Scenario-centered approach | Learner real needs | Indicators as pedagogical strategy |

the student; (5) *Activity* includes education/training, work and service record and products; (6) *Transcript* contains record of the academic performance of the student; (7) *Competency* describes the skills the learner has acquired; (8) *Interest* details the hobbies and other recreational activities; (9) *Affiliation* entity stores the data concerning the relevant cohorts, groups or class, in which the learner is a member (10) *Secure key* registers the passwords, certificates, PINs and other authentication keys; (11) *Relationship* contains the relation between other core data structures.

*PAPI Learner Standard* is a specification which describes a subset of useful learning information with the aim of facilitating the communication among cooperating systems. By means of this proposal it is possible to create and build a personal learner information repository, (i) to promote data portability of student information, (ii) to take into account information regarding the security, privacy and integrity and (iii) to provide more personalized and effective activities. The *PAPI Learner Standard* identifies the following six information types in its specification: (1) *Learner contact information* contains aspects related to administration information (*names*, *contacts* and *addresses*), (2) *Learner relations information* includes the relationships of a specific student to others (e.g., *classmate*, *teacherof*, *instructoris*, *belongsto*), (3) *Learner security information* stores the security credentials (*passwords*, *private keys*, *biometrics*, etc.), (4) *Learner preference information* contains data about the *language*, *elegibilities* and *preferences*, (5) *Learner performance information* stores the information about the performance of a learner, and (6) *Learner portfolio information* which collects learner's works to justify his/her skills and achievements.

### 2.3. Educational modeling languages (EML)

EMLs Specifications constitute a significant portion of this work. They contain the learning design models describing how a unit of learning is organized. EMLs facilitate, for instance, the representation of activity characteristics and learning objects. The use of EMLs in this work is justified by the fact that they formally describe pedagogical scenarios and resources. Besides, several EMLs are considered standards, i.e., specifications which have been meticulously analyzed and designed to ease the maintenance, reuse and comprehension of information.

Hence, the most important EMLs were also analyzed focusing on whether they are standards and their main characteristics (see Table 1).

In the early 2000's, a consolidated EML proposal to describe and design learning content and environments was developed by Artacho and Maíllo [29]. This approach is based on the instructional design process and provided users with an easy interoperability, maintainability and reusability due to the technology-independent representation of a learning resource. It is composed of five levels of learning environment according to educational purpose, logistic, structural and activity definition aspects. The *Content* level is responsible for describing the educative elements taking into account the reusability, granularity and reference mechanism. The *Task* level represents basic educational elements to enable the student's learning, evaluation and interaction with the instructor. The *Structure* level involves the organization and composition of content and tasks. The *Planning* level comprises the temporal organization and the previous dependencies to perform an activity. Finally, the *Management* level includes the control of all the information related to the accesses and developed activities. Many researchers consider it as one of the most important EML and thus, many research works have been influenced by this proposal [35].

Later, Koper and Manderveld [30] developed an educational specification of units of learning. This work provides flexibility in the creation of different types of learning objects to support new paradigms of teaching/learning. It is based on a widely extended pedagogical meta-model that has influenced the main EMLs. It identifies the following axioms: (i) a person learns by acting within the environment; (ii) learning means that the student is able to perform activities in similar environments faster or performs the activities in new environments; (iii) the environment is composed of objects and living beings in a specific interrelationship; (iv) a person can be encouraged to perform activities if there exists the proper motivation, personal circumstances, context and environment; and (v) these axioms are equally valid if they are applied to groups. This specification details the importance of roles, learning objectives, prerequisites, environments, activities, activity structure, play, conditions and so on.

Koper et al. [36] also developed another proposal known as IMS Learning Design (IMS LD) which evolved from the previously described specification, in an attempt to integrate it with others IMS specifications. The proposal incorporates three different levels: (i) Level A includes learning objectives, roles, activities, activity-structures, environments, resources and methods; (ii) Level B allows the inclusion of conditions and properties; (iii) Level C provides a notification capability. This specification is a *de-facto* standard for the representation of any learning design allowing a large amount of pedagogical techniques. The IMS LD has been applied to many educative proposals over the last decade. Among the most important proposals, it is worth highlighting the development of a framework which facilitates the integration of software components into IMS LD [37] or the development of the LPCEL editor which provides a broad level of expressiveness for IMS LD based models [38].

Another proposal that specifies a meta-model to formalize activities emphasizing those strongly related to e-learning platforms emerged in 2006 to ease the modeling of collaborative learning situations [32]. This proposal differs from other specifications by the fact that pedagogical activities cannot be divided into a succession of tasks to be carried out. Besides, this work includes the concept of *Scenario* as the specification of a learning activity, i.e., scenarios specify the *wh-questions* related to an activity. Each *Scenario* provides students and instructors with resources, tools, services or instruments to perform or assess an activity. The specification is composed of the following entities in addition to scenarios: the *Activity Structure* organizes the progression of interactions between the participants; the *Participant Interaction* represents the exchange between the participants during the knowledge acquisition process; the *Participation Roles* entity involves the learners, instructors, tutors and so on; the *Activity Arena* defines the place where the activity is performed; the *Rules* concept describes preconditions and final conditions of an activity; the *Position* shows the reaction and perception of participants regarding an activity; the *Observables* entity represents the learners' trace of an activity.

Caeiro et al. [33] developed perspective-oriented EML (poEML) as a way to support the modeling of learning units. This EML is based on the principles of separation-of-concerns (divide and conquer), and activity theory (meta-theory that relates activities with the environment). The authors identified 13 perspectives that can be modeled using poEML (*structural*, *functional*, *participant*, *environment*, *data*, *tool*, *organization*, *authorization*, *awareness*, *interaction*, *order*, *temporal* and *causal*).

The last reviewed work related to EMLs was developed within the CAUSA project. It is considered a conceptual framework that allows us (i) to structure learning scenarios through a graphical environment, (ii) to reuse and (iii) to share practices. The model creates adaptable, instantiable, appropriate and understandable scenarios by the instructors. We consider this proposal complementary to EML as it provides methods and tools that facilitate task design activities. This model is currently used in the French secondary education system [34].

Taking into account the purpose of our work, non-standard-based EMLs might hamper the development and communication between ontologies. Thus, the system may suffer from lack of extensibility that is one of the main advantages of using ontologies. In addition to be compliant with standards and extensibility, other features have also been evaluated in this survey such as personalization and contextualization. We consider that most suitable EML for this proposal is the one based-on the IMS LD [31] due to the following characteristics: (i) it is a *de-facto* standard; (ii) it easily communicates with other modules; and (iii) it comprises three levels according to the needs in each educational system. At this point, it should be highlighted that IMS LD can be easily related to IMS Learning Object Metadata (IMS LOM[6]). Therefore, we use this standard to represent learning objects instead of others such as Dublin Core[7] or SCORM.[8]

### *2.4. Taxonomies of objectives*

Objectives are another core element related to the instructional design. The instructional design describes the method that enables students to achieve the learning objectives after carrying out a set of activities using the environment's resources. According to experts, objectives are responsible for associating generic skills to a particular knowledge to allow learners to demonstrate that they are able to solve certain kinds of problems. In this way, different taxonomies regarding students' skills used to represent the acquisition of knowledge have been established. Among them, the most popular taxonomy of objectives is the Bloom's taxonomy. It comprises three important domains: cognitive, affective and psychomotor. The *cognitive* domain includes the intellectual area and learning related to knowledge, comprehension and critical thinking [39]. The *affective* domain comprises the abilities of communicate and understand feelings, i.e., learning related to senses, emotions and personal growth in attitudes [40]. Finally, the *psychomotor* domain covers people's abilities to make voluntary movements, skills and actions [41]. The Bloom's Taxonomy has been revised and adapted multiple times. Therefore, a new reviewed Bloom's taxonomy was created by modifying and replacing some terms [42]. Marzano and Kendall [43] developed a new educational taxonomy based on Bloom's Taxonomy. Later on, a reviewed Bloom's taxonomy was adapted to new realities of the digital age by developing the Bloom's digital taxonomy [44]. Recently, it has been associated with the SAMR model to support instructors in the design, development and integration of technologies in the learning [45]. This taxonomy has been applied to different proposals, such as SM or Paquette ontologies [46].

Another well-known taxonomy is the *Key Skills*. This proposal identifies six key skills: (i) Communication; (ii) Application of Number (for instance, calculations or interpretation of results); (iii) Information Technology; (iv) Workings with Others; (v) Improving own Learning and Performance; and (vi) Problem-Solving. Although it is not currently maintained, it is widely used in the British education system [47].

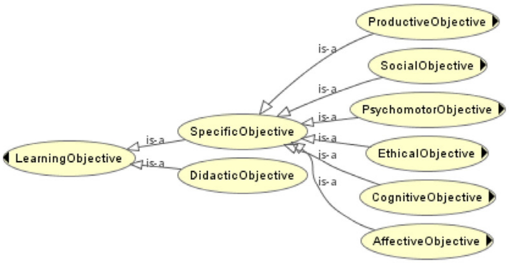
A more recent taxonomy of objectives was developed for the application of European Bologna process. The taxonomy is known as "Tuning" since it tries to find points of agreement, convergence and mutual understanding [48]. This proposal divides the competences according to their scope. Thus, it classifies the competences into specific (if they cover a number of thematic areas) or generic (if they are necessary for the proper performance of any profession). The generic competences are in turn categorized as instrumental, interpersonal or systemic in accordance with the related target.

The Comprehensive Adult Student Assessment Systems (CASAS) taxonomy of skills is another classification which distinguishes more than 360 basic competences. This taxonomy identifies essential competences for students and workers to be valuable members

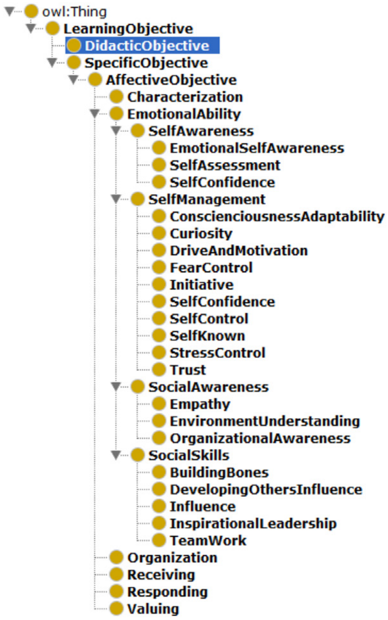
[6] https://www.imsglobal.org/metadata/index.html.

[7] http://hdl.handle.net/10421/3401.

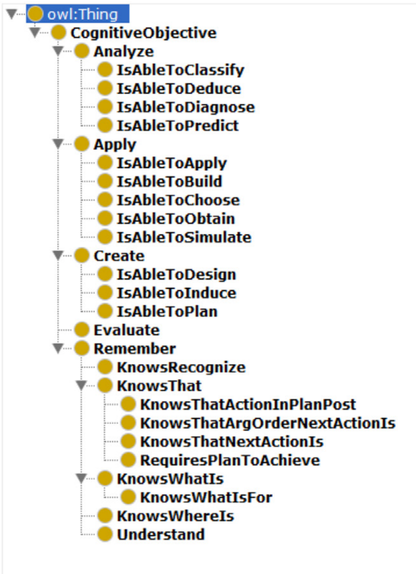
[8] http://www.adlnet.org/adl-research/scorm/.




(a) «LearningObjective» class hierarchy extracted with OWLViz plugin.




(b) «AffectiveObjective» class hierarchy.




(c) «CognitiveObjective» class hierarchy.

**Fig. 1.** General outline of the «LearningObjective» ontology.

of their family, community and work [49]. It is composed of the following categories: (i) Basic Communication, (ii) Community Resources, (iii) Consumer Economics, (iv) Health, (v) Employment, (vi) Government and Law, (vii) Math, (viii) Learning and Thinking Skills, and (ix) Independent Living.

Finally, the CPA Vision project deserves to be highlighted [50]. It was developed with the purpose of establishing basic competences especially relevant for professional environments. The project is composed of 26 interdisciplinary competences, for instance, Client and Market, Leadership Skills and Communications or Strategic and Critical Thinking skills, etc.

After analyzing the previous taxonomies, we transformed them into ontologies and specialized them following the NeOn guide adopted in this research (see Fig. 1). Fig. 1a represents the «LearningObjective » class hierarchy. Due to the dimensions of the ontology, we only provide as an example two of the most representative classes in the «LearningObjective» ontology (see Fig. 1b and c). This work organizes the skills into the following six classes:

- «EthicalObjective» involves the objectives related to ethical values. It is motivated by Rokeach's survey [51].
- «SocialObjective» represents objectives related to interpersonal relationships and it is influenced by CASAS, Key Skills and Paquette taxonomies [46].
- «ProductiveObjective» comprises the objectives relevant to undertaking a successful business or project and it is inspired in CPA Vision.
- «AffectiveObjective» represents objectives related to emotional aspects and attitudes and it is integrated by Krathwohl, Bloom and Goleman [52] taxonomies.
- «PsychomotorObjective» represents objectives related to physical, motor or coordination activities and it is based on Harrow taxonomy.

- «CognitiveObjective» provides information about knowledge structure objectives from reviewed Bloom's taxonomy and Paquette competences ontology.

## 3. Representation and ontology engineering of the ON-SMMILE

This work interrelates the four previously stated ontologies (Student Model, Performance Indicator, Assessment Rubric and IMS Learning Design) to develop a descriptive student model which provides instructors, and students themselves, the ability to get and analyze information about learner knowledge state. To carry out this interrelation, the first phase of the methodological guide, i.e., the ontology adaptation is followed. It consists of restructuring the class hierarchy of the ontology network and the instantiation of the elements involved in the scenarios, environments, units of learning, etc. In the first phase of this guide, we followed the NeOn methodology instead of other methodologies such as Methontology, On-To-Knowledge or DILIGENT. The reason is that NeOn is suitable for building ontology networks and it was developed to solve limitations from these methodologies. The main advantage of using ontology networks is modularization, reducing the impact of future changes and helping to understand the elements of a complex system. The limitations of other methodologies include the lack of guides (i) to develop ontologies by reusing or performing a reengineering process from other knowledge resources, and (ii) to contextualize an existing ontology by integrating it with others. Likewise, they do not explain the process of building ontologies with the same style and granularity of software methodologies [8]. After the specification of ON-SMMILE requirements and the search and choice of suitable ontological and non-ontological resources, the development continued with the modification of the ontologies, starting with those in SM ontology. The latter was adapted to the IMS standard and enriched with taxonomy skills. This section analyzes how the ontologies and properties from four different networks must be closely interlinked.

### 3.1. *Description of the ontologies*

The Protégé ontology editor has been employed to develop the whole ontological model using the Ontology Web Language (OWL) as an official W3C recommendation.

Fig. 2 shows an overview of the model considering all its ontologies. Since the model contains numerous elements, only the most representative classes, properties, relations and ontologies are shown in the figure (entities represented by white color). For the sake of clarity, we omit some relations (from the entities ended with an asterisk) such as «associatedLearningObjective» that relates «LearningObjective» and «Activity» classes or «hasLearningObject» which relates «Environment» and «LearningObject». Despite the fact that recursive relations in main entities such as «LearningObjective», «LearningObject», «ActivityStructure», etc., have not been illustrated to simplify the figure, these entities can indeed be recursively decomposed to represent more specific concepts such as learning objects (book, chapter, section, paragraph), objectives, activities, etc. We have upgraded and merged ontological and non-ontological resources, such as the SM, AR, IMS LD and PI ontologies to develop a model that supports information about students and their knowledge state as detailed below.

#### 3.1.1. *SM ontology*

The SM ontology network focuses on the characteristics and different types of knowledge about students. The network is composed of the following ontologies:

- «KnowledgeObject» contains the knowledge elements implicated in the learning process and classifies them as structural (proposition, property, relation, etc.) or procedural (plan, action, precondition, etc.). Consequently, this ontology can register, for instance, questions that require different level of detail such as "what is this object?" or "what is next action in the plan?", actions related to IVETs as «isAppliedToObjects» or «PickUpObject», interactions between tutor and student (give a hint), student's trajectories along the learning experience, etc.
- «LearningObjective» originally included the didactic and the specific objectives involved in the knowledge acquisition process, i.e., affective, cognitive and psychomotor. It was based on Bloom's, Krathwohl's and Harrow's taxonomies and it was key support to pedagogical diagnosis of students. After the requirement's specification phase, we have included the set of objectives described in Section 2.4 in the ontology.
- «StudentProfile» is responsible for representing the information related to the learner including personal data and features, such as demographic data or preferences. We carried out an ontology extension and restructuring to adapt the «StudentProfile» originally developed by Clemente et al. [53] to the IMS LIP [27]. The resultant ontology is composed of IMS LIP entities with the exception of the *Competency* class because its information is already registered in the «StudentState» and «StudentTrace» ontologies through certain properties of «ObjectiveState» and «ObjectiveTrace» classes.
- «StudentState» provides the student's performance during the learning sessions, i.e., whether students achieved or not the learning objectives or completion rate of activities. Assessment elements and properties interlinked with new «StudentProfile» have been added as properties or classes. This ontology can register emotional states (nervous, fear, etc) when the students are performing an action. It is particularly relevant in risky actions like the manipulation of a corrosive product in an immersive IVET.
- «StudentTrace» supplies a temporal register of the student's activity, such as action, session or objective traces. The rubric assessment trace and new properties added to the profile were included. We consider that the trace is very relevant for the network because in many occasions the sequence is as important as the final state. The «StudentTrace» is represented by means of the

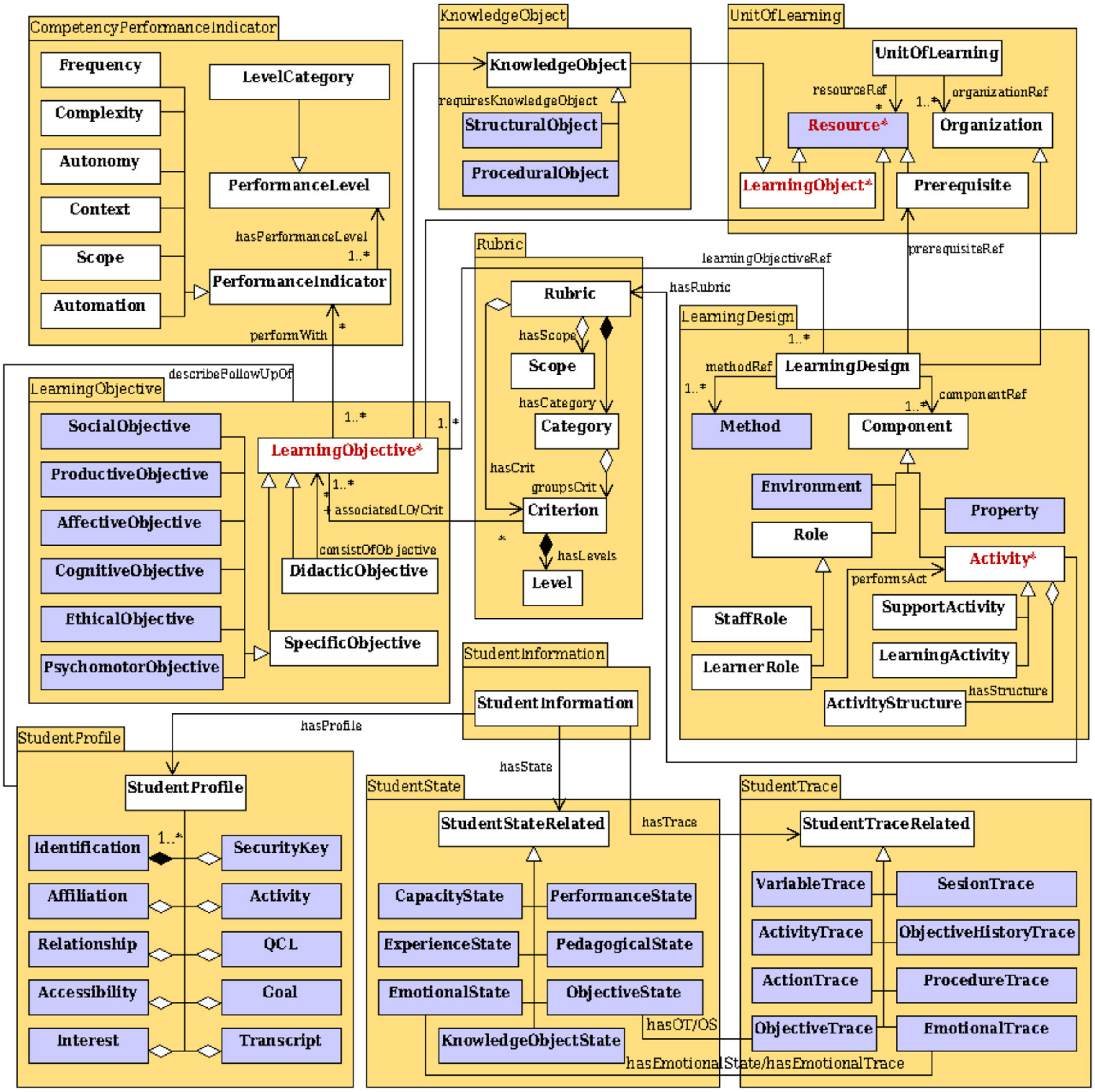



**Fig. 2.** Overview of ON-SMMILE.

student, the initial and the final time. In this way, «StudentTrace» supplies a temporal record of the student's activity, such as action, session, etc., as well as objective traces. Furthermore, this ontology can register and provide the tutor with information about the complete trajectory (path followed) of a student through the avatar's movements in an immersive environment. Besides, the trace of rubric assessment and properties associated to the profile, for instance, the affiliations or hobbies are now included into the ontology in an attempt to understand the evolution of student's interests. In the hierarchy of this ontology, an instance of a «SessionTrace» comprises «ActivityTrace» instances. This, in turn, contains «ProcedureTrace» instances. Finally, a «ProcedureTrace» instance contains «ActionTrace» instances. Each «ActionTrace» instance represents the execution (or the attempt of execution), by the student or the tutor, of a «PunctualAction». The ontology includes a wide range of taxonomy of actions (movements, interaction with objects or avatars, ask a question, etc.) so that, if an «ActionTrace» is of type «MovementActionTrace», then it will be also related to a «TrajectoryTrace» instance. The information on previous sessions including student traces (trajectories, executed actions, etc.) and cumulative state for each student (objective, states, etc.).

- «StudentInformation» represents an aggregate of all the information for a student, including the profile, state and trace.

Despite the fact that all previously described ontologies are related to students, it is worth clarifying that «LearningObjective» and «KnowledgeObject» are student independent ontologies as they allow the definition of instances which can be shared by multiple students. In this sense, these two ontologies can belong to both, the student and tutor models. We take them into account since they were originally used as a part of a student agent in an IVET as MAEVIF [54]. The MAEVIF architecture follows an agent-based approach that allows an easy configuration for different learning applications.

#### 3.1.2. AR ontology

In addition to the SM ontology, we reused an ontological resource related to learning evaluation. Rubrics are becoming one of the most important assessment instruments. They are scoring tools that list the criteria for a piece of work, or "what counts" and describe levels of quality from excellent to poor [55]. Rubrics also reduce the subjectivity and provide an auto-evaluation. The AR ontology presents the performance criteria and level in each activity [20]. It is composed of classes for assessment criterion, category, scope and scoring. The «Criterion» or dimension refers to the performance's aspects which are going to be observed and assessed. Each criterion has a qualitative and quantitative description about the level of achievement that the student is capable of demonstrating during the process, known as performance level. The «Category» class supplies the mechanisms to group the criteria in a same container. The «Scope» contains extra information about how a rubric is applied, i.e, it specifies whether: (1) the assessment is carried out individually by a domain expert, (2) the teacher or educator assesses or evaluates the work of a team, (3) the student work is assessed or evaluated by another individual learner or (4) the student uses the rubric to assess or evaluate his/her own learning. The «Scoring» class details the impact of rubric assessment in the final mark (scored or unscored).

#### 3.1.3. IMS LD ontology

Another ontological resource reused for completing this approach is the IMS LD specification. This is an XML specification that describes, among others, instructive activities from a pedagogic point of view. It is associated with basic IMS Global models and due to its extended use, the specification has been adapted to diverse means, including ontologies [31]. The IMS LD ontology supports the features of Level B and keeps the possibility of relating other IMS specifications [56]. It contributes to our student model providing the specification of resources and organization of a unit of learning. This ontology network is composed of the following classes: the «UnitOfLearning» class is responsible for defining a general module of the educational process, such as modules or courses, which integrates the IMS LD ontology and the resources. The «LearningDesign» class contains the main components of a learning process, such as the activities, roles or environments. It is also related to the «LearningObjective» and «Prerequisite» classes. Hence, it contains the outcomes when an element related to the «UnitOfLearning» is carried out. The «Metadata» ontology describes educational resources following a rigorous process, which greatly facilitates the interoperability and reusability between different platforms. Although this ontology is student independent, it allow us to define instances to be shared by several students such as the environment or activity. It is included on modular ontology network because the represented entities are very relevant in the process of student learning as well as its relationship to others ones such as Rubric, and specially significant to our proposal.

#### 3.1.4. PI ontology

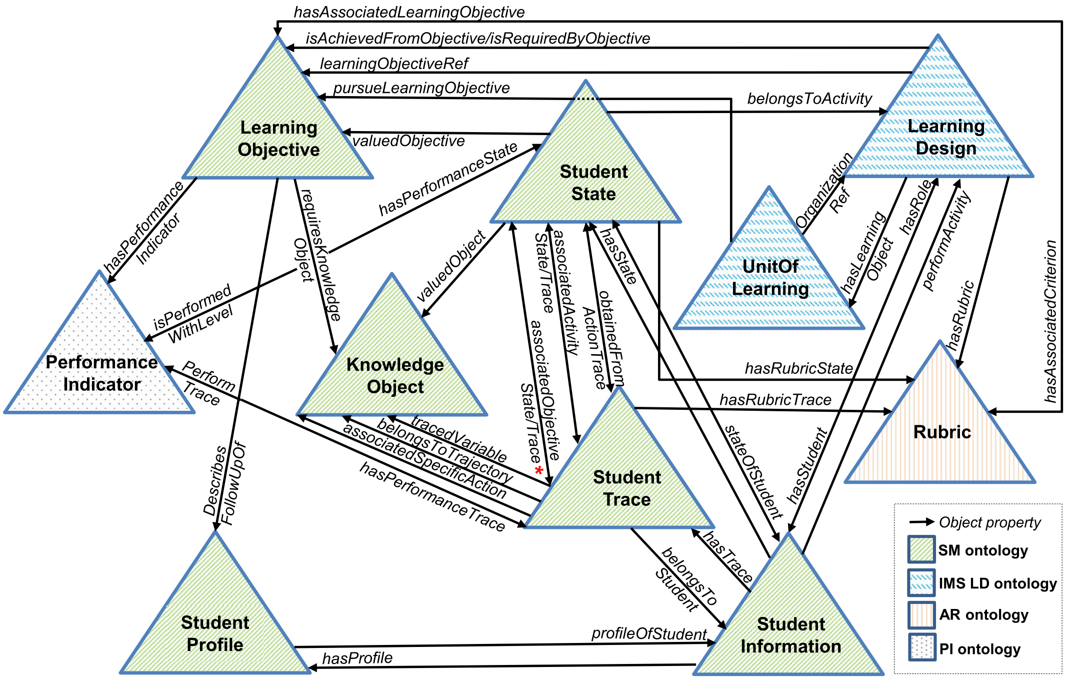
The last resource we have taken into account in ON-SMMILE is the PI ontology developed by Paquette [57]. We have reused and extended this ontology carrying out specialization activities and connecting it with IMS RDCEO standard model. Basically, we have associated the main PI class, «PerformanceIndicator», with the «LearningObjective» class inherit from SM ontology. «PerformanceIndicator» includes as sub-classes some interesting indicators, for instance, scope or frequency, which can be assessed thorough the «PerformanceLevel» class. As an additional improvement, the «PerformanceCategory» class has been added to create different performance levels based on qualitative or quantitative indicators.

The information retrieved from both PI and AR ontologies can be jointly analyzed to obtain a broader perception of the progress achieved by the students. Both ontologies enable instructors to know the quality performance of a student in a determined activity. While the AR ontology is centered around activity criteria, the PI ontology is focused on the performance level of learning objectives. For this reason, combining information from both resources, instructors can obtain accurate information about what are the real difficulties faced by students. Therefore, exploiting the information obtained from these ontologies improves students' adaptive learning.

### 3.2. Outlining the ON-SMMILE ontology

One of the main objectives of this work consists of extending the SM ontology with more properties related to students because we are interested in a student-centered approach. From this approach, we believe that the model should be updated to incorporate unspecified student's features. Thus, personal information about students, such as identification or demographic data, is represented in the original SM ontology by means of the properties «idStudent», «city» or «country» in «StudentProfile» ontology. However, it does not contain detailed information about other student's properties, for example, the accessibility represented by the «LearnerInformationProfile» class in the IMS LD ontology or research resource metadata adapted from Sawadogo et al. work [58]. Accordingly, we upgraded the original « StudentProfile» ontology following the Scenario 6 "Building ontology networks by reusing, merging and re-engineering ontologies or ontology modules" of the NeOn methodology [8].

The developed model is composed of new ontologies, classes, properties and datatypes, so, a restructuring of the network has been necessary to properly represent all the entities and relationships involved in the network. In order to facilitate the understanding of ON-SMMILE, a detailed explanation about the model is provided next and a higher level design diagram with the relationships among the ontologies is shown in Fig. 3.




* There are many others relations between StudentTrace and StudentState ontologies, for example, isRelatedToTrajectoryTrace or associatedSessionState.

**Fig. 3.** Modular decomposition of ON-SMMILE.

The main class defined in the ON-SMMILE model is «UnitOfLearning». This class is responsible for the definition of a general module in the educational process (e.g., a course or lesson) and it is related to the «Resource» and «Organization» classes. The first one describes «LearningObject», «LearningObjective» and «Prerequisite» classes. The second one manages the «LearningDesign» element, i.e., it represents the ontology which organizes components such as «Environment», «Role» or «Activity», all of them defined in terms of ontology classes.

According to the «LearningObject» class, we currently only consider in our model instances of «KnowledgeObject» class. However, in this regard other classes will probably be included as part of this ontology in future work. Likewise, the «LearningObjective» class classifies the objectives as didactic or specific according to the degree of specialization and each type of objective is characterized by different properties. For example, the achievement of a specific objective such as “work collaboratively with peer-group” leads to the acquisition of the didactic objective “obtain interpersonal communication skills and teamwork to work on projects and working groups”.

We also related the «LearningObjective» class to the «LearningDesign» ontology throughout its «Activity» class. «Activity» instances are classified as support of learning in accordance with their purpose. This class has, among others, a «Rubric» as possible assessment instrument. «Activity» instances are proposed by the «Staff» and performed by «Learner» instances.

The model stores all the information involving the «Learner» which includes the performance in an activity, profile, historical trace and current state. Many properties in the whole ontology were adapted to the «LangString» (data type with the language and text) allowing the internationalization of the network. As a result, instructors can populate the « Rubric» ontology with, for example, an internationalized rubric which will be shown in the language selected by the learner.

As it can be observed during the development of previous phases, we reused ontological and non-ontological resources previously described in Section 2. Then, a re-engineering process of non-ontological resources was performed to transform the selected taxonomies into ontologies. The existing ontologies were also updated extending or specializing them. Finally, interrelationships between ontologies have been established, resulting in the modular network ON-SMMILE. Thus, we achieved versioning and restructuring the original SM ontology using the NeOn methodological guide.

### *3.3. Verification of the ON-SMMILE ontology*

Once the ON-SMMILE ontology was completely designed and built, the next phase from the methodological guide must be applied. The second phase, diagnosis method adaptation, consists of a set of activities related to the adaptation of rules hierarchy, rules patterns and specific rules. Although this work is mainly focused on the model (and consequently this phase is out of scope of this article), the application of some rule patterns added in this second phase are presented in the case of study described in Section 4.3. Next, the ontology instantiation of the student and the ontology evaluation (validation and verification) which are

**Table 2**
Excerpt of the competency question.

| Competency question | Answer |
|---|---|
| What kind of objectives can be represented as specific in the ontology? | Cognitive, affective, psychomotor, social, ethical and productive. |
| What are the possible scope values of a given rubric? | Individual, Team, Peer and Self. |
| What performance indicators can be associated with a given learning objective? | Frequency, Automation, Autonomy, Complexity, Context and Scope |

**Table 3**
Excerpt of the learning objectives in «Activity_02».

| «description» | «type» |
|---|---|
| - Knows recognize a test tube in the scenario. | Cognitive |
| - Knows that the next operator in the plan is Goto. | Cognitive |
| - Know that args order in putting all the acid contained in the test tube into the glass with water is relevant. | Cognitive |
| - Is able to manage the stress in dangerous situations. | Affective |
| - Be responsible for cleaning and tidy the materials and instruments after using them. | Ethical |

closely related, are explained.

The verification process determines whether the product has been correctly built. In ontological terms, the verification process measures whether the ontology complies with the ontology requirement specification document (requirements and competency questions defined in the phase of ontology specification, concretely, in scenario 1 of NeOn methodology). Competency questions are defined as natural language questions that the ontology or ontology network should be able to answer [59]. They should be written by ontology engineers, answered by domain experts and used to extract the main concepts, properties relationships and axioms of the ontology. Hence, such competence questions and their answers can be considered as a kind of requirements specification [53]. Table 2 shows an excerpt of the competency questions form revisited in this phase to verify the new built in terms of ON-SMMILE ontology network. Similarly, the verification process checks the consistency and compliance with the ontology language, modeling mistakes, etc. For this purpose, we analyzed our network through the Pellet reasoner, available in Protégé, without finding any inconsistencies.

On the other hand, the validation process ensures that the designers are building the right ontology. Some domains of the original SM ontology were already validated in previous works with non-real students. For example, the learning activity concerning how the GUI of a text editor works [7], an experiment in a chemistry laboratory in which student's actions, trace and state were registered [53] or an experiment in a bio-technology virtual laboratory to test contradictory information [3].

## 4. Modeling a real case study

After developing ON-SMMILE, our efforts were focused on modeling a case study by using our ontology engineering solution in order to validate new elements.

### *4.1. Using ON-SMMILE to model a virtual environment learning experience*

Our proposal provides the flexibility and extensibility needed to model the student to an extensive range of educational environments based on the instructional design and constructivist learning model. With this objective in mind, the foundations of our work are based on (i) ontologies since they are easily extensible, (ii) rule patterns in order to adapt the network to different scenarios and (iii) an extensive taxonomy of diagnosis criteria [53]. Designing a model with these characteristics facilitates the monitoring of the students' interaction with the environment, the pedagogical diagnosis to infer the state of the student's knowledge from his/her performed actions in the environment and cognitive diagnosis to infer the knowledge objects from the relations between the objectives and objects in the ontology. In order to validate the changes and extensions added to SM ontology to form ON-SMMILE, the case study of modeling a virtual laboratory practice in a basic subject of a chemistry's degree has been updated to validate new properties and relationships [53]. For this purpose, we next describe the solution plan to prepare a 5% sulfuric acid dissolution.

As shown in Fig. 4, the solution plan enclosing the required actions that should be carried out by the student to conclude the activity successfully is compounded by a sequence of 11 actions. Some of them are compound actions in ontological terms as «Compound_01» which is an unordered block or a sequential block «Compound_02». In any case, compound actions are finally divided into simple actions such as "put on goggles" registered in the ontology as «Put_01».

Next, we illustrate an example of modeling in the ON-SMMILE for the «Activity_02»: *Preparation of a 5% sulfuric acid dissolution*, one of the dangerous practices of the first unit of learning "Virtual Basic Laboratory". Table 3 shows a summary of some of the real learning objectives set for this activity. In this context, ON-SMMILE was populated with instances that belong to the «LearningObjective» subclasses. For example, «KnowsRecognize_1» is an instance of «KnowsRecognize» class, which belongs to the «CognitiveObjective» hierarchy. This instance has the property «description» set to "Knows recognize a test tube in the scenario" which can be achieved, for instance, by the «associatedSpecificAction» «Put_05» or «Put_07».

In addition, the activity has an associated rubric tool for assessing the level of performance achieved by a student for each evaluation criterion specified in the practical assessment. This activity is associated with an analytic rubric based on point range. The

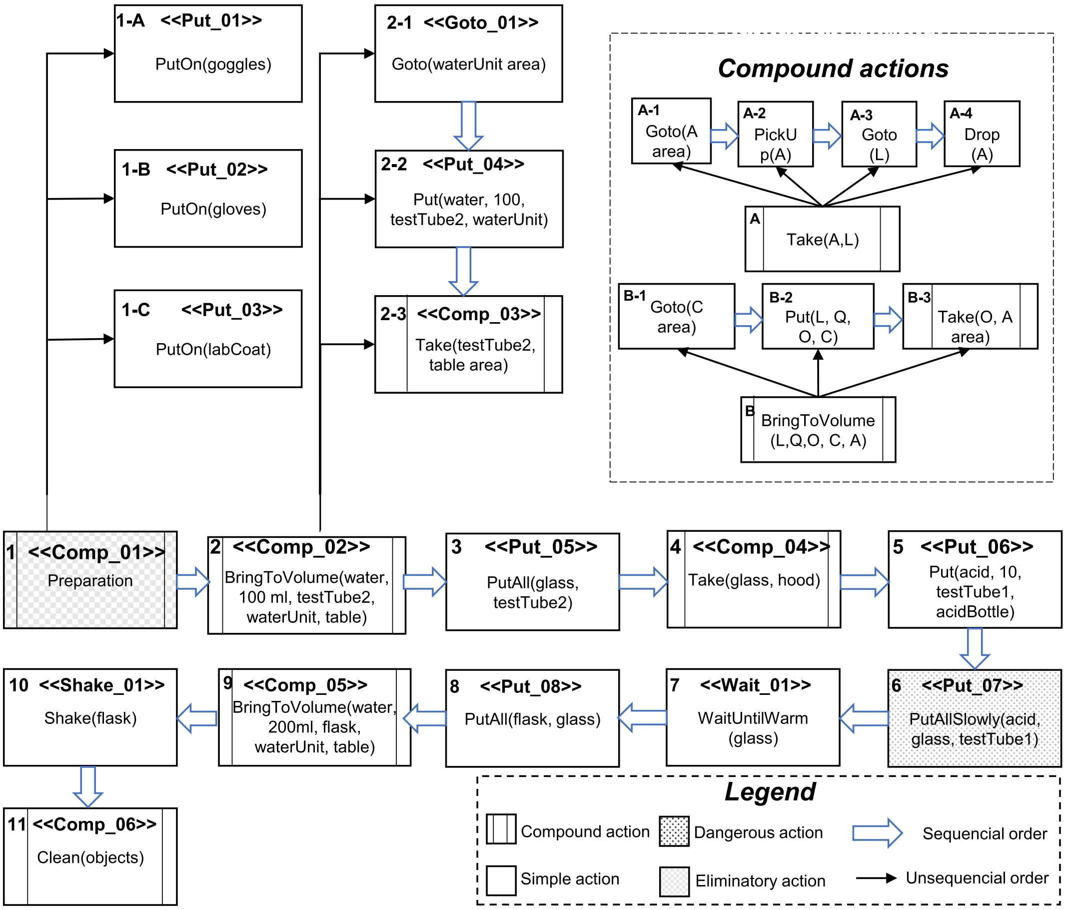



**Fig. 4.** Plan of «Activity_02»: "Virtual laboratory practice".

**Table 4**
Rubric for the activity *preparation of a 5% sulfuric acid dissolution.*

| Criterion | Performance | | | |
|---|---|---|---|---|
| | Very Low | Low | Standard | High |
| «**Criterion_01**» Respect safety regulations and good laboratory practice | The student respect less than 20% of the safety regulations and good laboratory practice. [0–5] | The student respect less than half of the safety regulations and good laboratory practice. [6–10] | The student respect at less half of the safety regulations and good laboratory practice. [11–15] | The student respect more than 80% of the safety regulations and good laboratory practice. [16–20] |
| «**Criterion_02**» Understand the importance of the preparation process | The student unknowns information about two or more required resources and needs help to use them. [0–10] | The student unknowns information about one required resource and needs help to use them. [11–20] | The student knows the information about all required resources but needs help to use them. [21–30] | The student is able to prepare the required resources for the experiment without help. [31–40] |
| «**Criterion_03**» Elaboration of the dissolution | The student is not able to deliver just in time any resultant composition. [0–10] | The student delivers the resultant composition but it does not meet the minimum preset criteria. [11–20] | The student delivers the resultant composition and it meets the minimum preset criteria. [21–30] | The student delivers the resultant composition and it meets the recommended preset criteria. [31–40] |

tutor, who designed the rubric shown in Table 4, considered that most of the criteria were assessed according to four levels: "Very low", "Low", "Standard" and "High". Nevertheless, flexibility is an essential property in the AR ontology since activity assessments are represented in percentages or performance levels. As a result, the ontology takes into account each criterion individually and provides the mechanisms to assign them to different measurement scales.

At this stage, it is worth noting that we intend to evaluate both the SM enhancements as well as the connection between ontologies. Considering that this ontology network can be applied to multiple environments, we decided to model an Intelligent

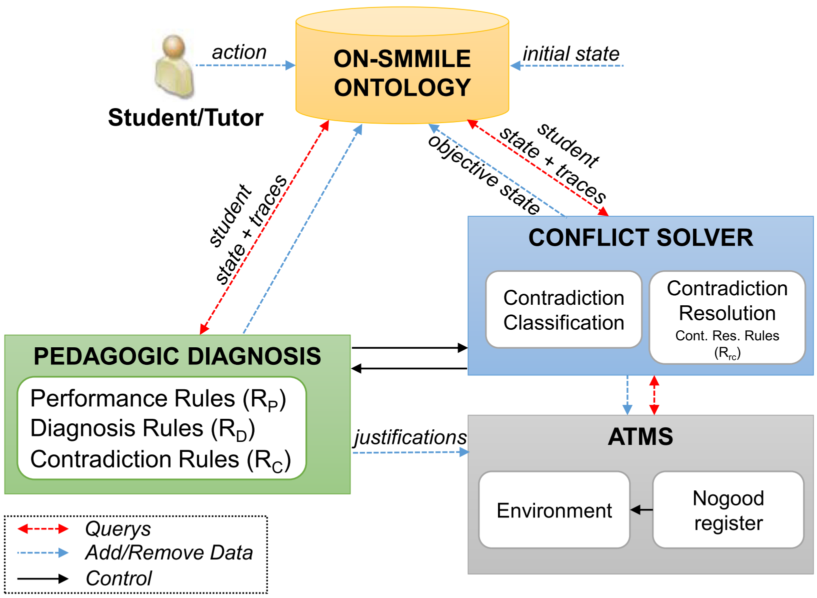



**Fig. 5.** Diagnosis method architecture.

Virtual Environments for Training/Instruction (IVETs) as our initial case. We chose an IVET since key information pieces for these environments are supported in the ontology. Concretely, VEs can be specially useful for allowing students to perform exercises that require expensive resources in the real world, or entail considerable risks. This is particularly beneficial in dangerous, expensive or long experiments or practices reducing the risks and providing more complete and accurate information about the learning process. In this way, this ontology network can, for example, model biotechnological experiments, simulation of difficult-to-reproduce environments such as spacewalking for astronauts training, foreign language activities, etc.

In addition to the ontologies, a set of SWRL rules was developed in this work to infer information concerning to the student's knowledge level. These rules are closely related to PI and AR ontologies due to the fact that the original SM ontology supports a non monotonic diagnosis method including a series of rule patterns arranged in an extensive taxonomy of diagnosis criteria using Jena framework[9] [53]. At this point, it should be highlighted that the diagnosis process can be complicated by the fact that students often learn or forget knowledge. Consequently, the knowledge assumed (or not) in the past can differ from current situation. We next describe a summary of the diagnosis method architecture.

### *4.2. Diagnosis method architecture*

The diagnosis method (see Fig. 5) is composed of the following modules:

Pedagogic Diagnosis (PD) is responsible for inferring the state of the student knowledge from his/her actions in the VE (registered in the ontology as traces of behavior). This functionality is supported by a set of diagnostic rule patterns such that, according to the contents of the SM ontology in every moment, infers what learning objectives have been achieved (or not) by the student.

Conflict Solver (CS) is responsible for two main tasks: (a) classify the contradictions that arise in the state of the student's knowledge objectives, and (b) resolve the type of contradictions.

ATMS is a widely known system for supporting belief revision [60]. It is employed to update the content of the SM ontology when the assumed state of an objective is refused and it is also necessary to retract the application of some diagnostic rule. Therefore, it is responsible for controlling the consistency of the assumptions used by the PD module and determine the beliefs held at any time in terms of the ontology (i.e., learning objective states).

The generic process is as follows. Each time an action is performed by the student or tutor in a learning session, some diagnostic rules are triggered in the PD based on the state of the SM ontology. The inferences made by this module are communicated to the ATMS in terms of justifications that are registered by it. If during the diagnosis process any contradiction arises between states of the same learning objective (detected by triggering the contradiction detection rules), the inconsistency will be classified and resolved by the CS. The resolution of a contradiction entails the following steps:

1. The contradiction is also notified to the ATMS as justifications. The ATMS obtains the environment that supports the contradiction and stores it in the so-called *no-good register*.

[9] http://jena.apache.org/.

2. The PD module invokes the CS to manage the contradiction. For this purpose, the CS performs the following steps:
   (a) Classifying the contradiction of a certain type using some classification rules.
   (b) Solving the contradiction by firing some resolution rules. The result is to establish what learning objective states should be updated in the SM ontology.
   (c) Updating the ATMS to take into account the deletion of the objective state and to reject all the inferences made from it.
   (d) Updating the SM ontology using the ATMS.

After the resolution of a contradiction, the PD may continue reasoning from the updated state of the SM ontology. At this point, it should be noted that a more detailed explanation of the diagnosis method regarding the ATMS can be found at Clemente et al. work [3].

### 4.3. Applying the model diagnosis for tutoring

At this time, by means of the original student model enrichment with information regarding objectives and rubrics, the instructors can obtain support for tutoring by two complementary methods. The first one consists of diagnosing the objective's state (non monotonic diagnosis indicated above) from the performed actions. The second method tries to detect failures from the rubric and the assessment of student's performance according to different criteria. The instructors can employ any of the two methods (or a combination of them) to recommend students a personalized learning process according their current student's state. Next, some examples of diagnose as an aid on the decision-making of the tutoring related to the previously designed learning experience are described.

When a new course is created, the ontology must be populated with learning activities, learning objectives associated with each activity as well as knowledge elements involved in the learning objectives and personal information about each student (student profile). As initial state for all the following examples, it is assumed that this learning experience (see Fig. 4) has a weak complexity and it is performed in a familiar context of work. For example, the instructors have decided that the action 1, consisting mainly of "putting on the laboratory garments", is an eliminatory action because safety is essential in a chemical laboratory. For the same reason, they consider action 6 "put slowly all the acid from the glass into testTube1" («Put_07») as a dangerous one. In addition, instructors suppose that the «acquired» property for all the learning objectives is initially set to *unknown*[10] and an objective will not be considered completely achieved if the number of times that it has been demonstrated does not reach a certain reliability level (considering the values of properties « levelCurrentReliability» of the concept «SpecificObjectiveState» and «levelReliability» of the concept «SpecificObjective»). As an additional task in this initial phase, instructors must reach an agreement about how to evaluate the «factorActivityKnowledge» property from «ActivityState» class as well as the initial configuration of the activity's limits to determine the experience level in the activity. These properties are configurable since they depend on the kind of activity and the learning environment. In this example, instructors agree that each objective must be achieved at least 2 times to be considered completely achieved, the «factorActivityKnowledge» property will be calculated through the rubric to diagnose the student's quality in the activity and the limits from *limit1* to *limit4* are set equal to 2, 4, 6 and 8 as threshold to establish novice, beginner, intermediate and expertise level experience respectively.

**Example 1.** The first student carries out on time the actions of «Activity_02». They were all satisfactorily performed and without tutor's assistance except for the action 6 consistent in "putting slowly 10 ml of acid from testTube1 to the glass with water" («Put_07», see Fig. 4). In this case, the student asks a basic question to instructor about the next action in the plan before to properly complete it. «Ask» class is defined in the «KnowledgeObject» ontology as «PunctualAction». In this regard, several types of questions («WhereIs», «WhatIsNextActionInPlan», etc.) and different question levels (basic, general and advanced questions) are taken into account in the model. Along this activity, after each action execution is registered in the ontology, multiple diagnostic rules are frequently triggered, and as consequence, conclusions are inferred about student knowledge state [7]. For example, the student's question about next action before action 6 lets us assume, among others, that the student is cautious and does not know what the next action in plan is.

After successfully completing the activity's plan on one or more sessions, at the end of the diagnosis process execution, it is assumed the student has obtained a high score in all the associated rubric's criteria (see Table 4) strengthening the positive conclusions previously obtained. As a result of the rubric score, the «factorActivityKnowledge» property is modified to *9.5* and performance rule $R_{P02}$ (see Rule 1) is triggered. The firing of this rule $R_{P02}$ allows the instructor to assume that the student has an expert experience level in the activity if the value of his/her «factorActivityKnowledge» property in the activity is greater than the *limit4* value. Consequently, a human/software tutor can recommend the student to deal with a more complex learning experience as tutoring strategy.

[10] The «acquired» property can take the values: *true* (the system believes the student has achieved the objective), *false* (the system believes the student has not achieved the objective) and *unknown* (the system does not know anything about the objective achievement).

$$\begin{aligned} R_{P02}:\ & \texttt{StudentInformation(?x)} \ \wedge \\ & \texttt{hasActivityState(?x, ?activityState)} \ \wedge \\ & \texttt{factorActivityKnowledge(?activityState, ?quality)} \ \wedge \\ & \texttt{swrlb:greaterThan(?quality, limit4)} \ \wedge \\ & \texttt{stateExperienceActivity(?activityState, ?experienceState)} \rightarrow \\ & \texttt{experienceLevel(?experienceState, "expert")} \end{aligned} \tag{1}$$

**Example 2.** The second student performs correctly the activity plan up to the action 3 («Put_05»). After that, she "puts 10 ml of sulfuric acid in the testTube1", corresponding to the action 5, without performing action 4 known as («Compound_04»). This action consists of "going to the glass area", "pick up the glass", "going to the hood area" and "drop the glass". As a result of this omission, the diagnostic rule $R_{D05}$ (see Rule 2) is triggered among others. The objectives: (1) "the student knows that the applied operator *Put* is later in the plan" and (2) "the student does not know that the next operator in the plan is *Goto*" are inferred to be achieved by means of this rule. Focusing on this second objective the state instance of the objective "*knows that the next operator in the plan is Goto*" in the ontology is modified from the property «acquired» = *unknown* to «acquired» = *false*. Taking into account that substances as sulfuric acid should be treated under a hood to limit exposure to hazardous or toxic fumes, it is considered the action would have only a slight risk if it were executed in a real environment instead of the IVET. Consequently, the tutoring strategy decides to give a second chance to the student without any hint or other tutor support. For this sequence of actions, it should be noted that other more strict tutoring strategies can be also applied at this point if it is considered that there is some risk to continue the activity.

In this second attempt, suppose that the student repeats the actions making again the same mistake. Rule $R_{D05}$ (see Rule 2) is triggered again. As there is an instance in the ontology associated with this objective state with property «acquired» set to *false*, the AddSM action updates the ontology increasing in 1 the value of «currentLevelReliability» property. Consequently, the tutoring strategy decides that the student is not well prepared for this practice. As a consequence, the tutor takes the control in the remainder of this activity providing the student with feedback about the mistake and the execution of the rest of planned actions. At this point, the «interruptedByTutor» property pertaining to the «ActivityState» class is updated from *false* to *true*.

$$\begin{aligned} R_{D05}:\ & \texttt{IF Apply(actX)} \ \wedge \\ & \texttt{NextActPlan(actY)} \ \wedge \\ & \neg\, \texttt{Eq(actX, actY)} \ \wedge \\ & \texttt{ActPlanPost(actX)} \rightarrow \\ & \texttt{AddSM(Know(ActPlanPost(actX)))} \ \wedge \\ & \texttt{AddSM(}\neg\, \texttt{Know(NextActPlan(actY)))} \end{aligned} \tag{2}$$

As a consequence of this diagnostic process, it is inferred the student has achieved the objectives related to the first three actions with a high or standard performance level. Nevertheless, she has not achieved the objective "*knows that the next operator in the plan is Goto*" as there is an instance of this objective with «acquired» property set to *false* and «currentLevelReliability» property to value *2*. Since the tutor takes the control of the activity, the rule $R_{P01}$ is triggered. This performance rule is able to assume that the student gets a novice experience level in an activity if the tutor decides to interrupt the student session (for example, because of he/she performed a dangerous action wrongly). In ontological terms, the *novice* level is registered in the «experienceLevel» property from the «ActivityState» class belonging to the «StudentState» ontology. Through the firing rule $R_{P01}$ (see Rule 3) is assumed that the student has a novice experience level in the activity and accordingly, the student does not meet the requisites to pass. For this reason, the tutor could recommended that the student repeats a previous learning experience regarding the basic concepts of this practice.

$$\begin{aligned} R_{P01}:\ & \texttt{StudentInformation(?x)} \ \wedge \\ & \texttt{hasActivityState(?x, ?activityState)} \ \wedge \\ & \texttt{stateExperienceActivity(?activityState, ?experienceState)} \ \wedge \\ & \texttt{interruptedByTutor(?activityState, true)} \rightarrow \\ & \texttt{experienceLevel(?experienceState, "novice")} \end{aligned} \tag{3}$$

**Example 3.** The third student executes correctly the first five actions of the activity plan. Next, he "puts the water of the glass into the *testTube1* with acid" instead of "putting all the acid contained in the *testTube1* into the glass with water". After executing this action, rule $R_{D07}$ (see Rule 4), among others, is triggered. The $R_{D07}$ represents that "if the student applies an action operator that involves a tuple of a relation among several objects and the operator and objects of this action are the same as the next action in the plan but the order of the objects in the tuple is incorrect" then, it is inferred that (1) the student does not know that the arguments order is relevant, and (2) he does not known the correct order of the arguments. We will focus on the second objective. As it has not been previously assessed, its state in the ontology before the firing rule was «acquired» = *unknown*. After rule $R_{D07}$ is fired, the value *false* is assigned to property «acquired» and value *1* to property «levelCurrentReliability». It is important to empathize that the application of this specific action order could produce dangerous effects such as acid splash or explosion so, it is not only wrong, but also very dangerous for students. Despite of the fact the examples are being performed in an IVET where the inherent risk in dangerous actions like this one is avoided, the tutor interrupts immediately the student current session and recommend the student an in-depth review of the learning materials before trying the activity again. It should be highlighted that other more or less strict tutoring strategies can also be applied at this point as well as in the rest of the examples.

$$
\begin{aligned}
R_{D07}\colon \texttt{IF}\ \ \texttt{Apply(actX)}\ \ &\wedge \\
\texttt{IsOfType(actX, ModifyRelationAmongObjects)}\ \ &\wedge \\
\texttt{NextActPlan(actX}')\ \ &\wedge \\
\texttt{Operator(actX, opX)}\ \ &\wedge \\
\texttt{Operator(actX}', \texttt{opX)}\ \ &\wedge \\
\texttt{Eq(Args(opX, lobjX), Args(opX, lobjX}'))\ \ &\wedge \\
\neg\,\texttt{Eq(OrderArgs(lobjX), OrderArgs(lobjX}')\ &\rightarrow \\
\texttt{AddSM(}\neg\,\texttt{Know(ArgumentsOrderIsRelevant(actX}')))\ \ &\wedge \\
\texttt{AddSM(}\neg\,\texttt{Know(ArgsOrderInNextAction(actX}'))&
\end{aligned}
\tag{4}
$$

Due to the results obtained during the diagnosis process, the student has achieved a very low performance level in the objective *"know that args order in action 6 is relevant"*. Similarly to our previous example, by means of Rule $R_{P01}$ (see Rule 3), let us assume that the student has a novice experience level in the activity and the decision of recommending a lower complexity activity in a familiar context of work to remember basic concepts is embraced.

**Example 4.** The fourth student executes correctly the first 6 actions of «Activity_02» plan. After that, she does not perform action 7 "wait until the glass is warm" («Wait_01»). At that moment, action 8 does not meet its precondition «Precondition_08», i.e., *the temperature of the glass must be below a particular threshold in order that the student does not burn the hands*. However, she tries to apply inappropriately action 8, "put all the dissolution from the glass to the flask", so that rule $R_{D01}$ (see Rule 5) is triggered. Consequently, the objectives "the student does not know that operator *PutAll* requires as precondition «Precondition_08»" and "the student does not know what the next operator in plan is *WaitUntilWarm*" are inferred. Focusing on the first objective, let us assume the state of the objective is modified from *unknown* to *false*.

$$
\begin{aligned}
R_{D01}\colon \texttt{IF}\ \ \texttt{TryToApply(actX)}\ \ &\wedge \\
\neg\,\texttt{Meet(actX, preconditionY)}\ \ &\wedge \\
\texttt{NextActPlan(actY)}\ \ &\wedge \\
\neg\,\texttt{Eq(actX, actY)}\ &\rightarrow \\
\texttt{AddSM(}\neg\,\texttt{Know(ReqPrecond(actX, preconditionY)))}\ \ &\wedge \\
\texttt{AddSM(}\neg\,\texttt{Know(NextActPlan(actY)))}&
\end{aligned}
\tag{5}
$$

As a tutoring strategy, the instructor decides to give her a hint about preconditions of operator *PutAll* and a second attempt to the student. This time, the student performs the right action according to the plan and finishes without making any other mistake throughout the rest of the activity. Therefore, the state of previously stated objective changes from false to true, that is, an inconsistency arises between both objective states. At this point, it should be highlighted that, exactly, the firing of a contradiction detection rule identifies the contradiction and the ATMS is informed by means of a justification. Then, the ATMS obtains the environment supporting the contradiction and stores it in the *no-good register*. Additionally, the firing of diagnostic rules is also notified to the ATMS by means of justifications to create, with all above-mentioned justifications, the ATMS data structures which allow the diagnosis method to reason non monotonically with the appropriate support of the ATMS system.

In addition, the CS is invoked. Its task is to classify the contradiction by using rule $R_{C01}$ (see Rule 6) as a contradiction between objectives states caused by a *student's mind change*. The antecedent of this rule is fulfilled: the student receives a hint of the tutor where he/she does not achieve an objective and, after that, the student achieves the objective and without objective' state cycles detected. Then, the CS resolves the contradiction by means of the rule $R_{RC01}$ (see Rule 7). This rule states: if there is a mind change, a forgetfulness or ignorance contradiction then, it is assume the current state (*true*) prevails over previous state (*false*). The objective state with «acquired» set to *false* is eliminated and the CS requests the ATMS to retract the assumed ATMS node representing the firing of Rule 5 ($R_{D01}$). As a consequence, the state of ATMS nodes derived from this assumed node switches to *out*.

$$
\begin{aligned}
R_{C01}: \texttt{IF}\;\; & \texttt{ThereIsContradiction(objX)} \;\wedge \\
& \texttt{LastStateAssumed(objX, stobjX)} \;\wedge \\
& \texttt{IsAchieved(stobjX)} \;\wedge \\
& \texttt{ObtainedByHint(stobjX)} \;\wedge \\
& \neg\,\texttt{ThereAreStateCycles(objX)} \;\rightarrow \\
& \texttt{ContradictionType(objX, mindChange)}
\end{aligned}
\tag{6}
$$

$$
\begin{aligned}
R_{RC01}: \texttt{IF}\;\; & \texttt{(TypeContradiction(objX, mindChange)} \;\vee \\
& \texttt{TypeContradiction(objX, forgetfulness)} \;\vee \\
& \texttt{TypeContradiction(objX, ignorance))} \;\wedge \\
& \texttt{LastStateAssumed(objX, stobjX)} \;\wedge \\
& \texttt{PrevStateAssumed(objX, stobjY)} \rightarrow \\
& \texttt{SetCurrentObjState(objX, stobjX))}
\end{aligned}
\tag{7}
$$

Once the student has finished the second activity attempt, she has obtained a high score in the «Criterion_01» and a standard level in both «Criterion_02» and «Criterion_03». As a consequence of these results, the «factorActivityKnowledge» value is modified to *7* and rule $R_{P03}$ is fired (see Rule 8). This rule allows the instructor to infer that the student obtains an intermediate experience level in the activity if her «factorActivityKnowledge» value is between *limit3* and *limit4*. For this reason, the tutor may recommend her either to perform (1) an activity with similar complexity but in an unfamiliar context of work, or (2) a more complex activity in a familiar context of work.

$$
\begin{aligned}
R_{P03}: & \texttt{StudentInformation(?x)} \;\wedge \\
& \texttt{hasActivityState(?x, ?activityState)} \;\wedge \\
& \texttt{factorActivityKnowledge(?activityState, ?quality)} \;\wedge \\
& \texttt{swrlb:greaterThan(?quality, limit3)} \;\wedge \\
& \texttt{swrlb:lessThanOrEqual(?quality, limit4)} \;\wedge \\
& \texttt{hasExperienceState(?activityState, ?experienceState)} \rightarrow \\
& \texttt{experienceLevel(?experienceState, "Intermediate")}
\end{aligned}
\tag{8}
$$

## 5. Discussion

As it has been previously stated, the hypothesis of this work suggests that a suitable organization of the information concerning the learning process contributes to improve the educational performance by the means of monitoring, diagnosis or supervision (adding to the above-mentioned decision-making in conflict or anomalous situations during learning process). For example, the methodological adaptation used to create a new student modeling using the SMMILE ontology and its modified diagnosis method enables the non-monotonic inference of objective's state along the learning process. It can be applied in the development of a competence-based recommender system to provide students and tutors with fine-grained or coarse-grained suggestions about the suitable learning objectives. In this way, this research provides instructors with a student model covering a broad spectrum of issues related to the progress of students during learning units to guide them adaptively. In order to evaluate this model, we next analyze the obtained results.

From a theoretical perspective, a key feature in a wide variety of learning environments is flexibility. A flexible model should be able to support traditional, distance or blended education systems, individual or collaborative learning, real and virtual scenarios, and so on. Likewise, the elements within the model have to be easily reused since many concepts or resources are applied to diverse domains. For instance, knowledge objects (hood, flask, goggles, etc.) represented in the model and used in the IVET of previous examples, may be easily re-used not only in other chemistry practices, but also in other different domains such as the training of laboratory staff in a pharmaceutical company. Similarly, different objective types such as *Knows where is a certain object*, *Is able to build a particular plan –to solve an activity–*, etc., should be easily re-used in these domains or units of learning. Another essential characteristic in a student model is *extensibility*, as the educational system is continually evolving to consider new teaching strategies, adapting their system to new environments or technology, defining new concepts, etc. Regarding these characteristics, the model presented in this work can be applied in a broad range of educational learning environments and activities due to the main contribution of this work, i.e., the creation of a new ontology network that combines, extends, enriches or standardizes other proposals. Besides, the incorporation of rules patterns related to the new entities of the model enables the inference of information and facilitates the diagnosis and decision making progresses. Consequently, student's information can be updated facilitating the just-in-time tutoring for each student. From this contribution and as a future line of work, we intent to design more complex systems such as recommender systems since they take advantage of existent information for recommending new elements.

As far as activities are concerned, we consider that the model is useful for the following reasons: (i) activities are related to objectives and rubrics, (ii) activities in our model are easily adaptable to many environments and domains, and (iii) tutors can easily supervise the learning progress from, among others, the student's performance in each activity.

## 6. Conclusions and future work

This work described Ontology Network-based Student Model for MultIple Learning Environments (ON-SMMILE), a new semantic web-based model to assist instructors in the tutoring decision making during the student learning process. The model combines consensual resources in education, such as IMS Learning Design, Student Model ontology network, Bloom taxonomy, etc., with a non-monotonic pedagogic/cognitive diagnosis method in an attempt to enhance the supervision process. Given the fact that our ontological model reuses or enriches standardized, adaptive and validated resources, the possibility of using ON-SMMILE in many types of education environment including e-learning, traditional, virtual environments, blended learning, game-based learning, etc., as support of the learning process represents an improvement in the current state of the art because no other approaches concerning student model and diagnostic rules allow the treatment of so much information in so many different kinds of educational environment.

Another interesting benefit of this model resides in the possibility of applying diverse data processing techniques. For example, once instructional designers create educational experiences, they can assess the progress, provide students with feedback and diagnose the learning progress during the performance of the activity through inference rules. The combination of monitoring and data processing techniques applied to education makes possible to get a broader and adaptive automated vision regarding the student's learning.

Concerning possible future lines of research, it should be noted that ontologies have been employed as representation formalism. Extending the current model with the NeOn methodological guide will contribute to a wider student model that will arrange all outstanding characteristics for educational area. In this regard: (i) other IMS Global specifications can be incorporated to the model, such as the ePortfolio, Question and Test; (ii) from the previous point, the creation of an assessment ontology covering other alternatives of learning assessment, not just rubrics, will be added in future revisions of our work and (iii) ON-SMMILE provides instructors with student's knowledge state and his/her learning to enhance the supervision process. This way, the two methods explained here can be combined to extract hardly deductible information such as finding the actions that were wrongly performed related to a rubric criteria. This entails a potential contributing source of indicators which enables to assume, for example, the creation of a competence-based recommender system which assists the tutor and the student during the learning progress.

In this regard, we will continue adapting the rule patterns, extending the diagnosis to include more aspects regarding rubrics and competences and designing a taxonomy of recommendation criteria for the development of the previously-mentioned competence-based recommender system. This system will take advantage of the ON-SMILE ontology, essentially competences and student performance, and will take into account the benefits of current recommender systems obtained from a systematic literature review in this context. Finally, an empirical validation with real students will enhance the ON-SMMILE ontology network architecture by detecting its missing gaps. Although different fragments of the proposed model were validated in this and previous works, we will complement the validation with more cases in the future. For instance, testing the verbal and non-verbal behavior with real students for procedural learning activities mainly focused on the psychomotor domain.

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