A Semantic Framework for Knowledge Management in Virtual Innovation Factories

Claudia Diamantini[1], Domenico Potena[1], Maurizio Proietti[2], Fabrizio Smith[2*], Emanuele Storti[1], and Francesco Taglino

[1]Dipartimento di Ingegneria dell'Informazione, Università Politecnica delle Marche - Via Brecce Bianche, 60131 Ancona, Italy
{c.diamantini, d.potena, e.storti}@univpm.it

[2]National Research Council, IASI - Viale Manzoni 30, 00185 Roma, Italy
{maurizio.proietti, fabrizio.smith, francesco.taglino}@iasi.cnr.it

[*] Corresponding Author

Abstract

Knowledge management is a crucial aspect for enterprises that want to effectively cope with business innovation. However, the full control of the knowledge asset is often missing due to the lack of precise organizational models, policies, and proper technologies, especially in Virtual Enterprises (VEs), which are characterized by heterogeneous partners with different policies, skills and know-how. For such reasons, the need for technologies that enable knowledge sharing, efficient access to knowledge resources, and interoperability is felt as primary. This work proposes a semantics-based infrastructure aimed at supporting effective knowledge management for business innovation in VEs. Knowledge resources are formally represented and stored in a semantic layer, which is exploited by a set of semantic services for enabling efficient retrieval and reasoning capabilities to derive additional knowledge.

Keywords: business innovation, computational ontology, virtual enterprise, semantic knowledge management

Introduction

Among the most recent innovation paradigms, open innovation is gaining ground. Open innovation is defined as “a paradigm that assumes that firms can and should use external ideas as well as internal ideas, and internal and external paths to market" (Chesbrough, 2003). This definition recalls the notion of *Virtual Enterprise*, that is, a networked organization where different autonomous entities collaborate towards a common goal. In particular, we introduce the notion of *Virtual Innovation Factory* (VIF) as an innovation-oriented Virtual Enterprise whose goal is to support the *production* of innovation. The latter takes place in the *Business Innovation Space* (BIS), where active entities are, beyond the R&D innovation teams, final users, partners or even competing companies, and other actors operating outside the enterprise boundaries. Operational processes pertaining to the BIS define the core innovation value chain: sourcing raw ideas, transforming them into products (goods and services), marketing and delivering new products. Finally, processes for the planning and monitoring of innovation projects conducted in the BIS characterize the managerial level of a VIF. All these kinds of activities require intense collaboration, communication and interaction, and ultimately a high level of knowledge sharing among the involved autonomous actors. Indeed, knowledge is the main factor that enables continuous innovation in a world of rapidly changing markets, products, services and technologies (see, e.g., Nonaka, Toyama, & Konno (2000) for a thorough discussion of the notion of knowledge and its role in enterprise management). Efficient access to knowledge resources is however hindered by interoperability issues coming from fragmentation and heterogeneity of the involved players, their data, information and knowledge resources.

In order to overcome interoperability issues and enable knowledge sharing, we propose an approach based on *semantic technologies.* In particular, as the main contribution of the paper, we propose the design principles and preliminary prototype definition of the *Production and Innovation Knowledge Repository* (PIKR), a semantics-based repository for knowledge resources related to the Business Innovation Space where the VIF operates. The PIKR also stores and manages knowledge about the ordinary production activities which are relevant to the VIF. However, in this paper we will mainly focus on the innovation related aspects.

The PIKR is a virtual repository since resources physically reside locally, at VIF's partners, while the repository will host and manage an *ontology-based* image of such resources, as the result of their *semantic description*. The design principles of the PIKR descend from the analysis of user requirements and of the methodological framework elaborated within the European project BIVEE[1] that lead to the recognition of core elements to be semantically described, namely *Documents*, *Business Processes* (BPs) and *Key Performance Indicators* (KPIs), and the relations among them. Furthermore, the paper describes a set of services, enabled by the semantic representation, providing smart access to stored resources, facilitating the sharing of contents, and supporting the information and knowledge interoperability with the ultimate goal of supporting innovation project management.

The paper is organized as follows: the next subsections discuss the BIVEE Innovation Framework, provide an analysis of requirements for the PIKR, and briefly survey related work. Then, in section "Semantic Framework" the core PIKR ontologies are discussed. Section "Semantic Services" describes a set of functionalities for searching, querying and reasoning over knowledge resources and their use for supporting innovation management. Section "Technical Realization" introduces the architectural organization of the first prototype of the PIKR.

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[1] http://www.bivee.eu

BIVEE Innovation Framework

The BIVEE project elaborated the *Business Innovation Reference Framework* that works as the methodological framework to create and manage knowledge in the BIS. The frame work is characterized by the following elements:

- **Loosely structured processes.** Achieving innovation is a different venture each time and it may largely vary depending on the nature of the sought innovation. Despite this very unstructured nature of innovation processes, some invariants, at a general level, do exist. BIVEE proposes the notion of *wave* (see below) to articulate an innovation venture.
- **Human-centric, document-driven approach.** The absence of rigidly defined processes requires providing guidance and support to innovation teams without constraining their creative attitude. BIVEE proposes a document-driven approach, where the goals to be achieved are represented by a collection of knowledge assets to be constructed, mainly under the form of documents. For instance, knowledge about technical feasibility, potential markets, competitors, or skills required to achieve an industrial innovation, is typically explicated into suitable documents.
- **Collaboration and open innovation.** When an innovation venture starts, it is necessary to create a flexible, dynamic network of competencies, internal as well as external to the enterprise boundaries.
- **Innovation monitoring and assessment.** Given that innovation is a costly activity, it is necessary to realize an effective strategy to monitor the quality and validity of the idea, and then its evolution throughout the different waves. The Innovation Monitoring strategy of BIVEE is conceived with a "couching" and constructive approach, largely based on the definition of a set of KPIs.

Innovation waves organize the activities carried out during the innovation life-cycle. Four waves have been identified: *Creativity, Feasibility, Prototyping, Engineering*.

- **Creativity.** All the activities related to the creation of new ideas.
- **Feasibility.** The scope and the intended impact is defined, including a first account of technical and financial feasibility.
- **Prototyping.** The first implementation of the initial ideas, achieving a first full scale working model. Such a model is tested and analyzed to verify the actual performance and features, giving also the possibility to rethink some design.
- **Engineering.** Activities aimed at producing the specification of the final version of the new product (essentially the Bill of Materials and manufacturing procedures), ready for the market, and the corresponding production process.

For each wave, a number of activities to be carried out in order for a wave to be completed have been identified. Examples are: Idea Generation and Idea Analysis for the Creativity Wave, Resource Analysis and Feasibility Study for the Feasibility Wave, Resource Allocation for the Prototyping Wave, Build and Optimize for the Engineering Wave.

Each activity is further specified by providing the description of inputs and outputs in terms of knowledge chunks needed and produced by the activity, respectively, that will correspond to (part of) a document to be filled, in order for each activity to be completed. Finally, activities and documents are associated with a set of indicators expressing the quality of a document or the performance of an activity. An example of document related to the (output of) Idea Generation activity is “Idea Description”, while the activity can be evaluated by indicators like the Cycle Time or the Investment in Employee Development. The indicator Idea Yield is associated with the Engineering Wave, measuring the ratio between ideas created and ideas that get to production. The systematic organization of indicators and documents includes the definition of indicators categories and objectives, documents prerequisites and constraints, and so forth.

The above analysis of the framework is taken into consideration in the organization of knowledge within the PIKR and in the design of the services for knowledge manipulation.

Analysis of Requirements

The starting point of the PIKR specification is the analysis of requirements that stem from: (i) the Business Innovation Reference Framework, discussed above, whose basic elements have to be semantically described; (ii) the functional requirement provided by the BIVEE end-users. From the end-users point of view, the PIKR should enable managers to perform the activities listed below.

1) To evaluate ideas that are proposed within the VIF, to filter them, and hence to support the selection of promising ideas. This evaluation is based on specific project-related KPIs, which originate from the members' information systems and are analyzed along various perspectives.
2) To monitor the status of an innovation project and its evolution. Managers should have at their disposal both a dashboard providing an overview of project indicators and functionalities to dynamically zoom in a gauge for understanding the behavior of the related KPI, analyzing values of other indicators on which it depends.
3) To classify ideas. As BIVEE is an open innovation environment, new ideas are proposed and discussed by several users. Managers should be provided with functionalities facilitating the classification of ideas on the basis of comments and tags provided by users. Classification with tags, content and semantic annotation is performed on the ideas together with further semantic functions. When a number of

ideas are received, the tagging and classifying mechanisms help users to filter and group them using tags.

4) To discover similarity among ideas at any stage (i.e., wave) of development, for avoiding duplication and improving the overall efficiency of the innovation process.
5) To reuse experience from past projects, by looking at results of both successful and dead projects. Reuse calls again for similarity discovery among knowledge resources, e.g., documents related to similar topics, projects evolving in a similar way, projects involving same patents, and so forth.
6) To search for partners with specific competencies. In order to increase the recall of the search, partners with competencies partially matching the given ones should be also returned. For instance, if a partner is able to produce a finished table, he could be able to provide the parts of the table too.

A selected list of the identified functional requirements is reported below.

a) To take into account different kinds of enterprise *knowledge resources*, such as structured and unstructured documents, competencies, products, KPI definitions and data for monitoring running activities, business processes.
b) To allow the management of VIF knowledge resources by means of *classification* and *annotation mechanisms*, taking into consideration application domain content of knowledge resources.
c) To support *access* and *retrieval* of resources by means of advanced search functions, based on exact and similarity matching.

d) To keep track of *links* and *dependencies* among knowledge resources (especially among innovation-related documents) for supporting smart access and manipulation of knowledge resources.

e) To support the *evaluation of indicators* for assessing the status of the activities in a VIF.

f) To provide *reasoning capabilities* over enterprise knowledge resources (e.g., business processes) for supporting their re-use, assessment, and constraints checking.

g) To provide *collaborative mechanisms* for facilitating the participation of the largest number of players in the process of continuous optimization and innovation.

The requirements (a) and (b)are addressed by the internal organization of the PIKR, where the different ontologies allow the semantic representation of different kinds of knowledge resources (see Section “Semantic Framework”). Aspect (c), (d), (e), (f) are covered by semantics-based search functions and reasoning capabilities (see Section “Semantic Services”).

Requirement (g) is the objective of a future work aimed to support semantic social networking in the BIVEE platform.

Related Work

Hidalgo and Albors (2008) discussed a list of ten typologies of Innovation Management Techniques and associated methodologies and tools. These typologies cover the various activities carried out daily in an innovating company, like ideas generation, market intelligence, and cooperation management. Innovation project management is also taken into consideration and some associated methodologies, such as project portfolio management, enlighten the attention towards planning activities.

In recent computer science literature, tools and methodologies have been proposed to support creativity (Shneiderman, 2007), ideas creation by social media and crowdsourcing (den Besten, 2012; Poetz & Schreier, 2012), ideas management (Xu & Bailey, 2012), knowledge creation and elicitation (Christiaens, De Leenheer, de Moor, & Meersman, 2008), knowledge discovery for innovation (Wang & Ohsawa, 2013). Much less work is devoted to models and methodologies for monitoring efficiency and effectiveness of innovation activities and for innovation project planning, especially in collaborative environments. Adams et al. (2006) presented a review of the literature pertaining to the measurement of innovation management at the firm's level, reporting also "an absence of measures well aligned to the activities of the innovation process". A framework and a set of 26 KPIs for the measurement of innovation availability, efficiency and effectiveness has been proposed by Zheng, Chanaron, You, and Chen (2009). In this work, innovation in a firm is seen as a whole, ignoring the process of its creation. Reference innovation processes and related metrics are proposed by the Value Reference Model[2] (VRM), which explicitly addresses networked and cooperative enterprises.

Due to the centrality of knowledge within innovation processes, several works closely related to our approach have investigated the adoption of semantics-based knowledge management solutions in enterprise innovation context (Spinosa, Quandt, & Pires Ramos, 2002; Tammela & Salminen, 2006; Shvaiko, Oltramari, Cuel, Pozza, & Angelini, 2010; Ning, O'Sullivan, Zhu, & Decker, 2006; Penela et al., 2011; Liu, Raahemi, & Benyoucef, 2011). Spinosa et al. (2002) discussed the requirements and functionalities that should be provided by

[2] http://www.value-chain.org/en/cms/1960

an IT-based framework to support the life cycle of knowledge in networked organizations, i.e., to recover the individual knowledge and transform it into products and services that can be exploited by the organization. The work of Tammela and Salminen (2006) reports about an open semantic infrastructure for supporting enterprise interoperability by which speeding up common innovation of products and services. They adopt a narrower perspective than ours, dealing only with semantics for enabling collaboration. Shvaiko et al. (2010) reported about a framework for enabling (territorial) innovation based on the so-called innovation tripole (three main stakeholders: final users, enterprises, research centers). The adoption of semantics-based knowledge management techniques is finalized to competence search among available actors. The system proposed by Ning et al. (2006) present semantics-enabled functionalities for browsing and searching innovation information within a Virtual Enterprise. This system is based on a common and shared ontology where innovation information is classified into five categories, without regard to innovation processes and performances. The work of Penela et al. (2011) focuses on managing enterprise collective knowledge, acquired through a microblogging layer and lifted by combining semantic indexing and search of messages and users. The paper considers textual messages only, as a source of information. Liu et al. (2011) proposed a socio-technological approach to human-centered knowledge sharing (considering heterogeneous knowledge resources, both explicit and implicit) in dynamic virtual enterprises. Although that paper shares many concepts and ideas with the present paper, it focuses on the management of documents only. At the best of our knowledge, no work considers the formal representation of innovation processes and indicators.

PIKR Semantic Framework

The mission of the PIKR is to create a semantics-based unified view of the information and knowledge created and transformed within the Business Innovation Space where the VIF operates, by providing a semantics-based infrastructure for

- the representation of *Digital Documental Resources* (DDRs) in terms of shared ontologies;
- the enactment of reasoning and searching functionalities on the annotated DDRs.

We identified the following core elements to be semantically described. *Documents*, which are concrete footprints of all kinds of activities, both at production and innovation level; *Business Processes* (BPs), which describe all the activities related to the development of innovation projects and their implementation in production processes; *Key Performance Indicators* (KPIs), for monitoring the progress of innovation projects and the related operational activities. Besides the aforementioned core elements identified in the BIVEE Business Innovation reference Framework, knowledge related to the specific Application Domain is taken into account in terms of actors and their competencies (which refer to the capabilities of the VIF and its members) and business related information, such as bill-of-materials and other production constraints, production techniques, patents and so forth.

To this end, the structure of the PIKR is organized into two semantic layers:

- a federation of ontologies to deal with the aforementioned kinds of knowledge, collectively referred to as the *Intensional* PIKR (I-PIKR);
- the semantic representation of the information relevant to VIF members in terms of the I-PIKR ontologies, through Semantic Descriptors (SDs), which constitute the *Factual* PIKR (F-PIKR).

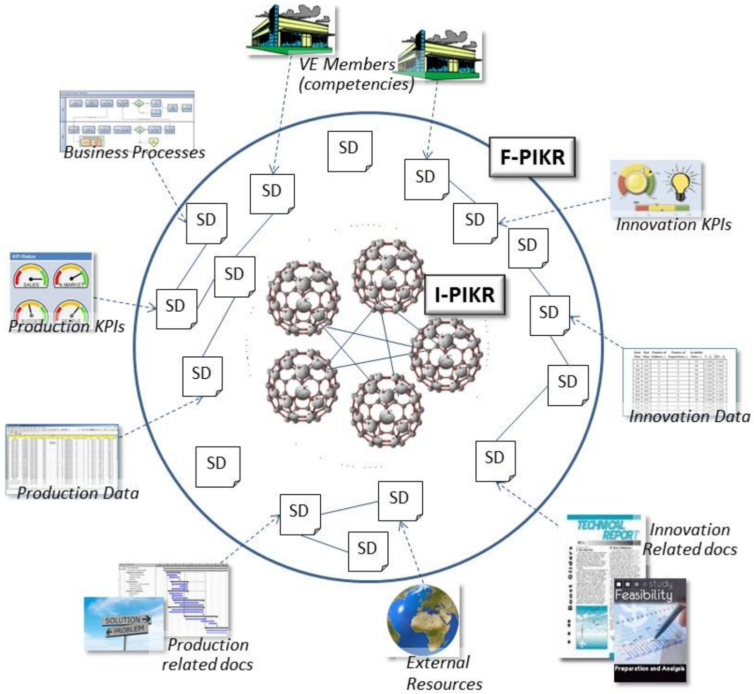

Figure 1. Overview of the PIKR semantic framework

An overview of the PIKR semantic framework is given in Figure 1. Different DDRs pertaining to the BIS are semantically annotated by using the ontologies in the I-PIKR, maintained in the F-PIKR and made available to the VIF again by means of semantics-based services. The effect of the semantic description of the DDRs is also to establish links among different DDRs in accordance with the dependencies defined at ontology level. This provides an integrated image of the DDRs which is seen by the PIKR through their SDs.

The ontologies in the I-PIKR are partitioned into *Knowledge Resource Ontologies* (KROs), which are independent of any application domain and provide the means for the representation of the main knowledge resources (Documents, BPs, KPIs), and *Domain Specific Ontologies* (DSOs), which provide the semantics of a specific business scenario. A number of relations are provided to establish links among the concepts defined in the I-PIKR ontologies, as depicted in Figure 2. KROs may refer to DSOs to align heterogeneous terminologies. Indicators can be related to the processes or documents they are intended to monitor. Documents in turn could report on processes and indicators, or produced and consumed by the processes which operate on them.

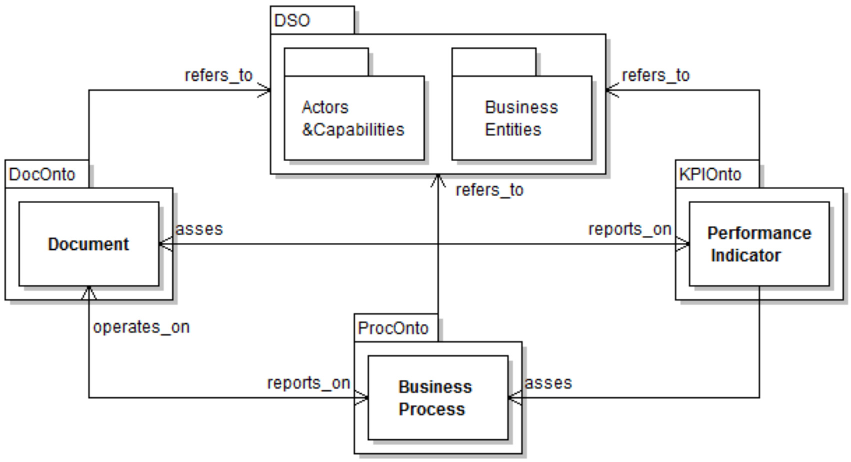

Figure 2. Main relationships among I-PIKR ontologies

SDs are instantiated according to the KROs to build up a formal and unambiguous description of the actual virtual enterprise resources, in order to allow the participating SMEs to achieve a uniform management of information despite their local divergences. For instance, the semantics of a business object related to a BP, let us say a "contour chair", may refer to a specific term of the furniture ontology; instances of the Organizational Dimension of an indicator, like "John Smith", can be linked to actors defined in the DSOs. Independently of their specificities, due to the different nature of the DDR types, the KROs aim to catch certain categories of information so that the Semantic Descriptor will be characterized by a common structure organized into the following sections:

- **Header**: provides traditional metadata like the ones proposed by the Dublin Core Vocabulary[3], and the link to the described informative resource assumed to be stored in a proprietary system;

[3] http://dublincore.org

- **Domain Specific Content**: provides a definition of the content explicated by an informative resource in terms of the DSOs;
- **Related Knowledge Resources**: collects links to related SDs, allowing the representation of semantic associations and dependencies among resources;
- **Extended Representation**: contains formal representations of particular resources (in particular, mathematical formulas defining KPIs, and workflow graphs defining BPs) to allow specific reasoning tasks;
- **External links**: links to resources external to the VIF available on the Internet (e.g., technical documentation, external policies or regulations).

Knowledge Resource Ontologies

The VIF members have different methods and tools to represent information and knowledge. In order for the PIKR to act as a common hub for the management of knowledge resources in a VIF, a crucial role is played by the KROs, which are briefly introduced in the following.

DocOnto: Document Ontology. In Virtual Enterprises, document transfer is one of the commonly used ways to exchange enterprise knowledge among parties. Digital documents consist of electronic matters that provide information or evidence, often in an unstructured or loosely structured form, mainly produced for human consumption, which can be of many different types, e.g., a report of a brainstorming session describing proposals of innovation ideas, a feasibility study, a model of a production process, a bill of material.

The document ontology (DocOnto) provides the formal means for the semantic categorization and annotation of the "documents" identified through the analysis conducted with the BIVEE end-users. This means defining in formal terms the schema of the document SDs, with their structure (which information is mandatory and which one is optional), organization (how the document content can be related to domain ontologies) and dependencies, (other resources which are related/included/required). An example of SD addressing a Technical Solution document is reported in Table 1.

Table 1. An example of DocOnto SD for the document *Technical Solution*

Doc:TechnicalSolution	
Header	
Title	Advanced HMI
Identifier	TS_AdvancedHMI
Description	System for the robot programming based on the 3d reconstruction of the inspected components
Responsible	Luca Lattanzi
Contributor	Matteo Piersantelli
Creation Date	13/06/2012
Format	ms-word
Language	Italian
Document Indicators	Readability=4; Technical Quality=4
Resource Link	http://bivee.eng/bis/loccioni/doc/proposedIdea21.doc
Title	Advanced HMI
Content	
Research Line	3D vision, cloud point, artificial intelligence algorithm, anthropomorphous manipulator
Beneficiary	Loccioni group
Technology	HMI
Novel Features	simple, intuitive
Advantages	3d reconstruction, optimal path, collision avoidance
Related Resources	
Part of	doc:IP_AdvancedHMI
Has budget	doc:BS_AdvancedHMI

A number of requirements have been considered in the creation of the DocOnto. Besides the suitability for the adoption in business realities, the ontology should also be generic enough to be used across different domains, be able to support interoperability, and require reasonable efforts for its maintenance and extension. To realize these goals, we rely on established standards and solutions. In particular, we adapted the Core Components Technical Specification (CCTS) methodology (UN/CEFACT, 2009), whose objective is to identify, capture and maximize the re-use of business information to support and enhance information interoperability. Following the CCTS approach, the DocOnto identifies the basic information entities (Information Items), i.e., semantic building blocks that can be used for all aspects of data and information modelling and exchange. Complex data models for the business documents are constructed through the association and aggregation of information items.

The DocOnto applies several categorizations to the documents. Considering the organization of the VIF activities within the BIS, documents are associated to the four innovation waves characterizing innovation projects. Documents are also classified with respect to their role in the key processes they are involved in. For instance, a document could be a *proposal***,** an *assessment*, a *feedback*, or a *report*. Finally, relations between documents are classified in terms of *dependencies* (e.g., *prerequisite_of*, expressing that a document is required in the production of another one), *decomposition* (e.g., *part_of*, relating an information item to a document) and *associations* (e.g., *related_to*, representing a generic, non-hierarchical, semantic association between two documents). In Figure 3 exemplary document categories are depicted, together with some relations among them.

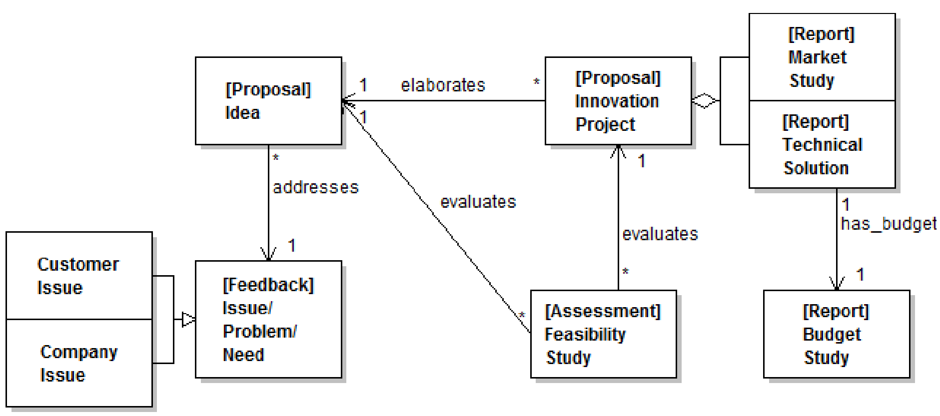

Figure 3. Excerpt of document categories and relations defined in the DocOnto

ProcOnto: Business Process Ontology. The Business Process Ontology (ProcOnto) provides the means for representing and reasoning with process knowledge, by semantically representing Business Process (BP) models.

For the definition of the ProcOnto, we adopt the Business Process Abstract Language - BPAL (Missikoff, Proietti, & Smith, 2011; Smith & Proietti, 2013), a process ontology which provides constructs for capturing the structure and the behaviour of a BP represented according to a workflow perspective. BPAL supports the definition of a BP Schema, by means of constructs to represent activities and events, control flow dependencies, branching/merging of the control flow (inclusive, exclusive and parallel gateways), data flow, hierarchical decomposition of activities, pre-conditions and effects of activities. The main categories defined in the ProcOnto are shown in Figure 4. A BP Schema is equipped with a formal behavioral semantics, which captures the notions of state of the world and state updates, caused by the execution of activities, reflecting possible enactments of the BP (i.e., execution traces).

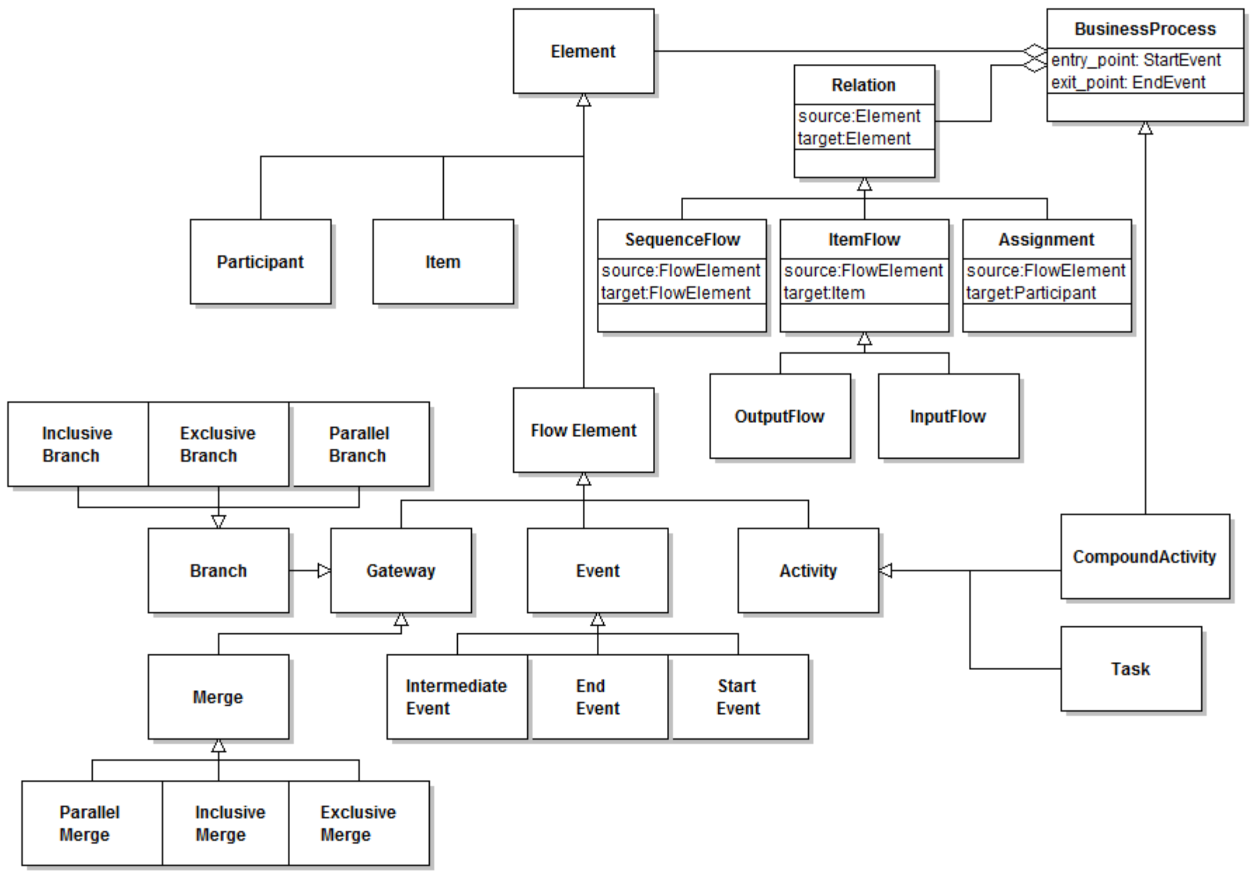

Figure 4. Excerpt of categories and relations defined in the ProcOnto

The ProcOnto thus encompasses modelling notions common to the most used and widely accepted BP modelling languages and, in particular, its core is based on BPMN 2.0 specification (OMG, 2011).

Now we introduce the main aspects of the ProcOnto by means of an example. The SD shown in Table 2, results from the annotation of a BP developed in the *release* phase of the *engineering* wave, and is related to the production of a specific chair model (Mod. 178), that is, an armchair with an embedded media-player. In particular, Table 2 reports an instance of the ProcOnto class *Activity*, representing the assembling of the components of the Mod. 178 armchair.

In the header section a number of self-explicatory meta-data are collected. The content section of a ProcOnto Activity is specified in terms of:

- a *terminological annotation*, which defines a correspondence between elements of a BP Schema and concepts defined in the DSOs;
- the *conditions* under which it can be correctly executed;
- the *effects* of its execution upon the state of the world.

Other resources that can be related to an activity SD encompass:

- the *participants* in the activity;
- the *control flow* dependencies;
- the *data flow* dependencies, describing inputs and outputs of the activity;
- the *performance indicators* (KPIs) associated with the activity for monitoring.

Table 2. An example of ProcOnto SD for the activity *Welding of pieces of Mod 178*

bpal:Task	
Header	
Title	Welding of pieces of Mod. 178
Description	The welding of pieces consists of performing the assembly of the components of the Mod 178, embedding a media player within a steel armchair
Identifier	proc: mod178_WeldingPieces
Source	http://bivee.eng/bis/aidima/mod178.uml/Welding_of_pieces
ConformsTo	UML Activity Diagrams
Wave	Engineering#release
Content	
TermRef	dso:Assembly AND ∃dso:component.dso:MediaPlayer AND ∃dso:component.dso:Armchair
Condition	dso:ErgonomicSteelChair(esc) AND dso:MediaPlayer(mp) AND dso:delivered(esc,man) AND dso:delivered(mp,man) AND dso:Manufacturer(man)
Effect	dso:Assembled(chair) AND has_part(chair,mp) AND has_part(chair,esc)
Related Resources	
Participants	controller → dso:ProductionManager, performer → dso:Manufacturer
Control Flow Dependencies	predecessor → proc: mod178_PiecesTransportation
Data Flow Dependencies	input → doc:DeliveryNote, output → doc:QualityControlSpecifications
Performance Indicator	performance →kpi:AverageAssemblyTime, reliability→kpi: ProductionFailureRatio, cost → AverageLotCost, scalability → kpi:DailyCapacity

KPIOnto: Key Performance Indicator Ontology. Several definitions of Performance Indicators, different for goals, domain of interest, degree of precision, and formalism, are provided, e.g., by international and national public bodies, in reference models like the Supply-Chain Reference Model[4] and the VRM. For the design of the KPIOnto and for the development of the Business Innovation Reference Framework, our approach aims to abstract over the general features of such models, with a particular focus on VRM which explicitly addresses networked enterprises. However, the KPIOnto allows us to describe indicators with different scopes: ‘global’ indicators, conceived to monitor the whole innovation project, and ‘local’ indicators measuring the performances of individual Enterprises. It is worth noting that the latter are needed to derive, namely to compute, the former.

Hereafter we give a summary description of the KPIOnto, whose main categories are *Indicator*, *Priority*, *Dimension* and *Formula*. Figure 5 shows these classes and the relationships among them. The KPIOnto taxonomy is similar to the VRM classification of KPIs, which in turn is related to the Enterprise area of intervention, e.g., *Corporate*, *Customer*, *Operation* or *Product*. However, multiple-categorization is allowed by the ontology, thus supporting more efficient indexing and searching functionalities.

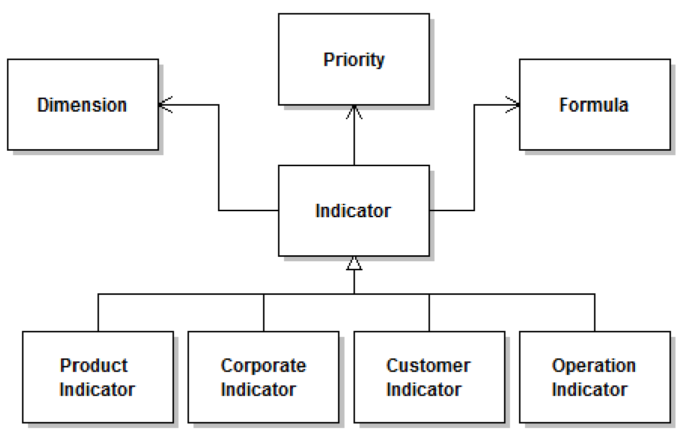

Figura 5. Excerpt of categories and relations defined in the KPIOnto

[4]http://supply-chain.org/f/SCOR-Overview-Web.pdf

Peculiarities of an Indicator in KPIOnto are: *unit of measure* as a reference to a concept of the Measurement Units Ontology[5] (MUO), represented through the UCUM standardized codes for the units of measure; *priority dimensions*, i.e., according to VRM, goals of optimization for which the indicator is used; as top-level classes of metric goals we use Reliability, Velocity, Adaptability, Cost, Asset, Innovation and Customer; *Dimensions* and *Formula*.

A Dimension is the coordinate/perspective to which the metric refers (e.g., delivery time and means of transportation). Referring to the multi-dimensional model used in data-warehouse (Kimball & Ross, 2002), a dimension is usually structured into a hierarchy of levels where each level represents a different way of grouping elements of the dimension (e.g., it is useful to group days by weeks, months and years). Each level is represented as a class in KPIOnto, related to its corresponding higher level through a part-of relation (e.g., a day is part-of a week, an department is part-of an enterprise). Such representation of dimensions enables usual analysis operations over indicators, namely *roll-up* and *drill-down*.

The semantics of an indicator cannot be fully given without the representation of its formula, which is the way the indicator is computed (Diamantini & Potena, 2008). To this end, each instance of the Formula class refers to MathML[6], a mathematical standard for describing mathematical notations, capable to capture both the structure and the content of a formula. The formal representation of the structure of a formula allows us to implement advanced reasoning services on KPIs that will be detailed in Section “Semantic Services”.

In Table 3the Semantic Descriptor for the KPI Idea Yield is shown.

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[5] Measurement Units Ontology, http://forge.morfeoproject.org/wiki_en/index.php/Units_of_measurement_ontology

[6]http://www.w3.org/Math/

Table 3. An example of KPIOnto SD for the indicator "Idea Yield"

kpi:Indicator	
Header	
Title	Idea Yield
Acronym	IY
Description	The percentage of ideas accepted into concept development
Unit of Measure	muo:ucom:UnitOfDim:percent
Content	
Metric goal	kpi:PriorityDimension
Dimension	kpi:TimeDimension, kpi:organizationDimension
Class	kpi:Program
Related Resources	
Assesses	proc:Wave_Engineering
Extended Representation	
Formula Presentation	<annotation-xml encoding=`MathML-Presentation'> ...
Formula Content	<annotation-xml encoding=`MathML-Content'> <apply><eq/><ci> IY1 </ci> <apply><times/> <apply><divide/> <ci>IAcc</ci> <ci>ICre</ci> </apply> <cn> 100 </cn></apply> </apply> </annotation-xml>

Domain Specific Ontologies. While KROs are designed to be applicable across different business domains, DSOs are related to the specific one at hand, that we represent in terms of three main components: (1) the involved **actors** (VIF members, potential clients, external partners), (2) business **objects** pertinent to the specific production reality, including **products** (services and goods) in the scope of the VIF, (3) key **technologies** available within the capabilities of the VIF.

Our experience with the BIVEE end-users (operating in the furniture and robotics sectors, respectively) revealed that part of this knowledge can be gathered from glossaries and standards already in use.

For instance, the product dimension related to the furniture domain can be covered by including the *FunStep ontology* (Sarraipa, 2009), based on the International standard for the information exchange FunStep (ISO 10303-236) and focused on the furniture and wood cluster (fabrics, accessories, materials, etc). FunStep defines a common vocabulary, expressed in a formal way according to the OWL standard (Hitzler, Krötzsch, Parsia, Patel-Schneider, & Rudolph, 2009), which captures the most used concepts inside the furniture and furniture-related industry, including properties and relationships between concepts.

We can also gather significant business terminology and a classification of technologies related to *robotics* through international standards such as the ISO 8373 standard[7], defining terms relevant to industrial robots operating in a manufacturing environment, or the International Vocabulary of Metrology[8], a common reference for practitioners involved in measurements activities.

However, besides all the aforementioned resources, the (often tacit) knowledge of people is the main source to be managed. In order to convert it into a more explicit and processable knowledge, we are following a collaborative ontology building methodology (Ludovici, Smith, & Taglino, 2013), built upon standard languages, such as OWL and SKOS[9], and supported by a software platform built upon a semantic Wiki. This methodology allows knowledge engineers, domain experts, and ontology stakeholders to cooperate for reaching a consensus on the suitability of the produced conceptual models with respect to the application domain at hand, and guaranteeing at the same time a formal encoding into a computational ontology.

Semantic Services

The PIKR provides a set of semantics-based services that enable the retrieval and the processing of information stored in the Knowledge Repository. These services support functionalities that facilitate innovation management within the Virtual Innovation Factory.

[7]http://www.iso.org/iso/home/st re/catalogue_ics
[8] http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2008.pdf
[9]http://www.w3.org/2004/02/skos/

In order to store and reason about knowledge resources in an effective way, the PIKR makes use of various knowledge representation formalisms and reasoning methods. Most of the conceptual knowledge defined in the I-PIKR and of the factual knowledge stored in the F-PIKR is encoded by using OWL (Hitzler et al., 2009), a de-facto standard logical formalism for ontology and meta-data sharing which extends RDF (Klyne & Carroll, 2004) and RDFS (Brickley & Guha, 2004). For encoding knowledge structures defined in the ProcOnto and KPIOnto, such as workflow graphs of BPs or mathematical definitions of KPIs, we use more sophisticated representation formalisms grounded in logic programming (LP) (Lloyd, 1987). In particular, we use the logic-based BPAL language (Missikoff et al., 2011; Smith & Proietti, 2013) for processes, and the algebraic language adopted by the PRESS equation solving system (Sterling, Bundy, Byrd, O'Keefe & Silver, 1989) for KPI definitions.

In this section we present the following basic semantics-enabled searching and reasoning provided by the PIKR:(i) *Searching*, (ii) *Querying*, (iii) *Consistency Checking*, and (iv) *KPI Reasoning*. The design and implementation of more complex services that can be achieved extending these basic services will be briefly discussed in the Conclusions.

The above facilities can be used for supporting the planning of innovation projects managed by the VIF. Usage scenarios include: (i) proposal of VIF partners to be assigned to a given task on the basis of the exhibited capabilities; (ii) retrieval of documentation reporting related previous experiences; (iii) search of best practices (e.g., in the form of BP models or rules) collected during the development of successful innovation processes; (iv) identification of the KPIs that can be computed for the whole VIF starting from a set of enterprises with their own indicators.

Searching

The PIKR provides a keyword-based search service, following an interaction paradigm similar to traditional web information retrieval engines, but characterized by the fact that the keywords come from the controlled vocabulary provided by the I-PIKR ontologies. The search function is based on *semantic similarity*, and implements the *SemSim* method presented in (Formica, Missikoff, Pourabbas, & Taglino, 2010).

SemSim requires that each DDR is associated with a collection of concepts (ontology-based *feature vector*) defined in a *weighted* reference ontology. The weight associated with a feature represents the probability that a DDR is annotated with that feature, and is computed by following the *information content* approach (Lin, 1998).

A search request has the following structure: {(*pr:rv*)*;*c**}, where:

- *pr* specifies a *target property* of the SD to be considered in the evaluation of the semantic similarity;
- *rv* is a *request vector* constituted by a set of concepts;
- *c* is a *constraint* formulated in terms of the value of an SD property that must be satisfied in an exact way.

For the given request, the search service returns a list of DDRs, ranked on the basis of the similarity of the corresponding SDs with the request. To this end, the *SemSim* engine first retrieves the SDs that satisfy the constraints *c**, and then evaluates the semantic similarity between the *request vectors* and the *feature vector* associated with each selected SD (considering the concepts associated with the *target properties*).

An example of application of the Semantic Search service is as follows. Suppose that during the set-up of a VIF for the development of innovative furniture, the user is interested in "*finding all the documents concerning the initial stages of the design of a piece of furniture equipped with an electronic device which have been issued in the last two years*".

The corresponding request is formulated by using terms defined in the I-PIKR, e.g.,

```
{content:[Furniture, Electronic_Device]; type=Document,
        creationWave=Creativity, issueYear>2010}
```

where

- `content` is the property that indicates that the concepts appearing in the request vector [`Furniture, Electronic_Device`] refer to the `content` section of the SDs;
- `type=Document`, `creationWave=Creativity`, and `issueYear>2010` are constraints that must be satisfied by the DDRs to be retrieved (i.e., "*documents*", "*concerning the initial stages of the design"*, and "*issued in the last two years*).

Rather than simply providing links to documents where the keywords are textually mentioned, the search engine will retrieve semantically related resources, such as `Proposed_Idea` or `Project_Proposal` documents (which are assumed to be defined in the Creativity Wave) about a `Sofa` with an embedded `Media_Player` (which are assumed to be defined in the DSOs as types of furniture and electronic devices, respectively).

Querying

Querying services allow the user to retrieve pieces of knowledge which exhibit some specified properties. Queries are asked in terms of the vocabulary and semantic relations provided by the I-PIKR ontologies, and the underlying reasoning engine returns a list of answers that satisfy all specified properties. These answers may consist of factual knowledge (SDs), intensional knowledge (ontological concepts in the I-PIKR), or references to resources (DDRs). The main differences between querying and searching are that the requests specified by queries can be much more complex logical expressions, and answers to queries satisfy those requests in an exact way, instead of up to a certain degree of similarity.

The PIKR querying service allows the specification of composite queries, possibly involving more than one kind of knowledge represented in the PIKR (e.g., DSO concepts, business process schemas, mathematical definitions of KPIs, business rules).

The PIKR provides a simple and expressive query language that extends SPARQL (Prud'hommeaux & Seaborne, 2008), the W3C standard for querying OWL/RDF resources. A query is an expression of the form:

`SELECT` `?x*` **`WHERE`** *comparison_predicate*

The **`SELECT`** statement defines the output of query evaluation. It consists of a (possibly empty) sequence of variables occurring in the **`WHERE`** statement. The **`WHERE`**statement specifies a condition that the output data must satisfy. The *comparison_predicate* is a Boolean combination of:

- predicates of the form $t(s,p,o)$ representing OWL/RDF triples, defined in the I-PIKR and F-PIKR;
- predicates representing properties of business processes and KPIs, defined in the ProcOnto and KPIOnto, respectively.

Queries involving OWL/RDF triples only, are processed by using standard evaluation engines for semantic resources in triple form, while queries involving also predicates different from

OWL/RDF triples are automatically translated into an LP representation (Abiteboul, Hull, & Vianu, 1995) and processed by a Prolog engine (see Section "Technical Realization").

To see an example, consider the following query, which may be useful in a situation where the evaluation of a given KPI alerts an unsatisfactory performance, and hence we want to retrieve the documents describing the activities that precede the underperforming one.

```
SELECT ?doc ?a ?b ?p WHERE alert(?b,?p) AND precedence(?a,?b,?p)
    AND t(?doc,reports_on,?a) AND t(?doc,type,Protocol)
```

The query evaluation engine returns the `Protocol` documents (`reports_on`) specifying the procedures related to activities `?a` that precede (`precedence`) the activity `?b` in the enactment of a process `?p`, such that the evaluation of a KPI related to `?b` raises an alert (`alert`).

Consistency Checking

The conceptual knowledge represented in the I-PIKR includes constraints of various types which specify the structure of the domain entities (*structural constraints*) and the way correct business operations are conducted (*behavioral constraints*).

Examples of structural constraints are the dependencies between documents, while behavioral constraints are business rules that express policies and internal regulations of the VIF, e.g., regulating the behaviour of the BPs, the definition/evaluation of KPIs and their interdependencies.

Consistency checking allows the user to verify the compliance of the factual knowledge stored in the PIKR with respect to the specified constraints. This is done by a logic-based reasoner that checks the consistency of the semantic descriptors contained in the F-PIKR with respect to the constraints specified in the I-PIKR. In the case where an inconsistency is found, the reasoner also provides a *witness* of the consistency violation (i.e., an explanation), by computing a set of semantic descriptors that belong to the current state of the PIKR and do not satisfy the given constraint. Constraints are specified by rules of the form

If *Premise* **then** *Conclusion*

meaning that if *Premise* is true, then also *Conclusion* must be true.

For instance, the structural constraint "Each *innovation_report* needs to be composed by a *project_proposal* and a *market_analysis*, can be formalized by the following rule:

if*innovation_report*(*x*) **then**

∃y,z. *project_proposal*(*y*) **and**

market_analysis(*z*) **and**

partOf(*x*,*y*) **and**

partOf(*x*,*z*)

If-then rules are then translated into LP clauses. For instance, the above rule is translated into:

```
inconsistent(X) :- t(X,rdf:type,innovation_report), not q(X).

q(X) :- t(Y,rdf:type,project_proposal),
     t(Z,rdf:type,market_analysis), t(X,partOf,Y), t(X,partOf,Z).
```

By evaluating the LP query

```
?- inconsistent(X).
```

the inference engine returns 'true' if the constraint is violated and 'false' if the constraint is satisfied. In the case where the constraint is violated the reasoned also returns an innovation_report X which is *not* composed by a project_proposal and a market_analysis.

Behavioral constraints can be modeled and verified in a similar way by using suitable predicates defined in the PIKR Knowledge Base.

KPI reasoning

The effectiveness and efficiency of innovation activities is monitored by analyzing KPIs of past and present projects. The KPI reasoning module provides inference services for supporting KPI elicitation (i.e., the identification of the KPIs suitable for a given VIF) by analyzing KPIs from different perspectives (e.g., organization and time dimensions) through OLAP-like queries. This module also supports the harmonization of the measures provided by VIF members which are needed for the evaluation of KPIs. Indeed, since measures can be originated by different data sources (e.g., proprietary information systems) from different enterprises in the VIF, they need to land on a reference representation compliant with the KPI formulas. Examples of heterogeneities between data definitions and required input for KPI evaluation could be in terms of naming (e.g., Customer_Requested_Date vs. Expected_Delivery_Date), granularity (e.g., aggregated vs. atomic data, different levels of aggregation), or structure.

Given the heterogeneities among partners, every time a KPI needs to be evaluated, a formula rewriting service is capable to find alternative ways to express the KPI formula, by browsing KPIOnto and by performing expansion/reduction/replacement of its terms with other formulas. In such a way it is possible to map an OLAP query, defined at VIF level, to local queries over indicators provided by enterprises.

As an example, to evaluate costs of innovation projects aggregated by product dimension, let us consider the following KPIs:

```
PersonnelCost = NumHours*HourlyCost*(Overhead+1)

InvestmentInEmployeeDevelopment = HourlyCost*NumTrainingHours
```

Let us also assume that an enterprise provides the following set of indicators:

{`InvestmentInEmployeeDevelopment`, `NumTrainingHours`, `OverheadRate`, `NumHours`}.

Although `HourlyCost` is not explicitly provided, it can be derived from the second formula through the rewriting functionality, thus allowing the calculus of `PersonnelCost`. Other analyses are made possible by exploiting links between KPIs and BPs.

In order to model and reason about KPIs, the PIKR makes use of a logic-based formalization of mathematical theories like algebra and calculus. The PIKR reasoning system is an adaptation and extension of the Rule-based Equation Solving System (PRESS) (Sterling et al., 1989) implemented in LP. Formulas encoding mathematical definitions of KPIs are encoded as axioms, while mathematical rules for the manipulation of formulas are encoded as LP rules.

Technical Realization

This section describes the architecture of the PIKR and the main technological aspects that are reflected in the first release of the PIKR software prototype. The architecture, as well as the technical implementation, have been conceived by following two main concepts: (1) *Service Oriented Architecture*, in order to have flexible and platform independent technological communication channels among the PIKR and the other software operating in the VIF; (2) *Linked Data principles***,** for exposing, sharing, and connecting pieces of data, information, and knowledge by using semantic web technologies and standards. In particular, following the Linked Data approach, the PIKR provides, on the one hand a set of reference structures (i.e., ontologies) for the semantic description of enterprise knowledge resources, and on the other hand semantics-based services for accessing and reasoning over such descriptions. To enforce the openness of the platform from a technical perspective, every knowledge fragment is identified by a URI, accessible via HTTP, described by RDF/OWL, and processable by reasoning services exposed as Web Services.

Figure 6 depicts the overall PIKR architecture, and its positioning within the VIF infrastructure. As previously stated, the PIKR is intended to provide semantic facilities to the VIF front-end which implements the functionalities to assist the innovation team in the management of an innovation project. Such functionalities, implemented by the components shown in the upper part of Figure 6, encompass: (1) the *set-up of the Virtual Enterprise*, with the definition of its business goals, capabilities, production plans, and so on; (2) definition of the *business models* needed for the enactment of the innovation project (e.g., BPs, Objects, Goals, Requirements, KPIs); (3) the support for the *enactment of the innovation project* along the four waves, for the coordination and planning of the activities conducted by the participant actors; (4) the *monitoring* of the progress of the whole project, in order to foster new improvements and further innovations. In doing this, the *VIF front-end* interacts with the *semantic layer* which offers a semantically enriched and machine-processable representation of the informative resources maintained by the *VIF back-end*. The latter is in charge of acquiring several kinds of resources from the Information Systems of the VIF members through the *Enterprises Data Wrappers*. Among the different kinds of resources handled by the *Storage System*, we consider particularly relevant documents, process logs and indicators collected from VIF members.

Semantic Wrappers are then responsible for handling the mapping between the data stored in the back-end and the corresponding semantic representation available in the semantic layer.

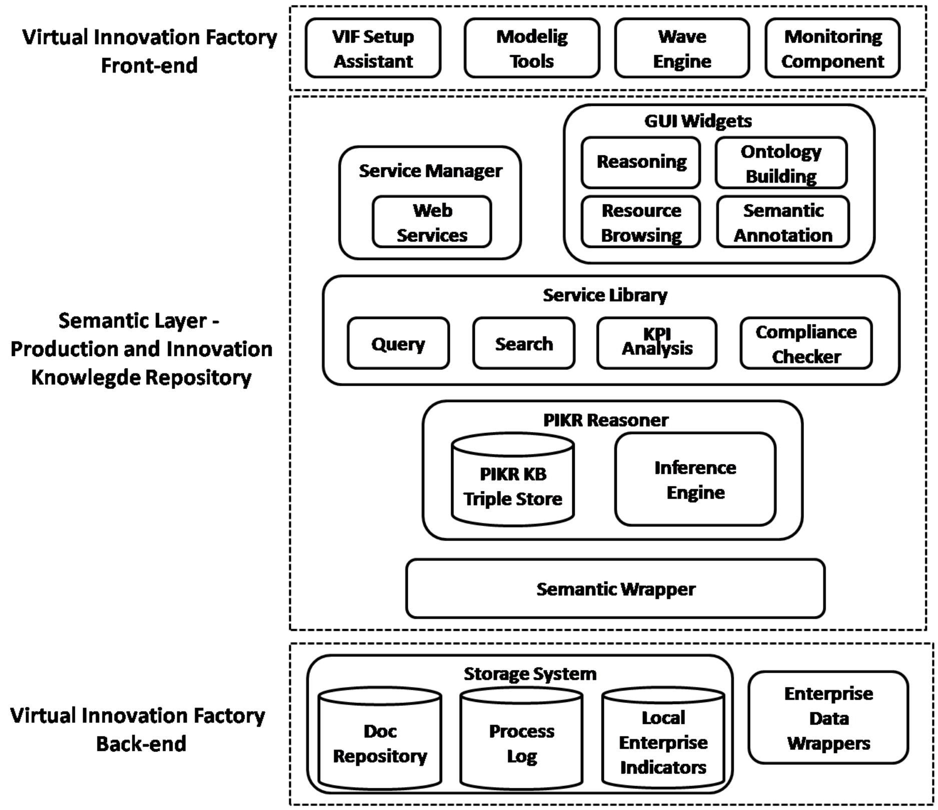

Figure 6. PIKR Architecture and positioning within the VIF infrastructure

The entry point for the PIKR reasoning functionalities is the *Service Library*. Several semantic services are implemented on top of the PIKR Reasoner and the semantic resources (SDs and ontologies) constituting the PIKR Knowledge Base (KB). The latter is stored in the *Triple Store*, providing basic storage and retrieval facilities for OWL/RDF data. The various reasoning methods that operate on the PIKR KB are implemented by the *Inference Engine,* and are made available through a Web Service interface, exposed by the *Service Manager,* and through the *PIKR GUI,* which enables user interaction through a wiki-like environment.

Service Library and PIKR Reasoner

The semantic services provided by the PIKR are implemented in the Service Library. The latter relies on the reasoning capabilities offered by the PIKR Reasoner, which is a LP reasoned connected to a Triple Store storing the PIKR KB. Having populated the PIKR KB, reasoning services are essentially performed by the modules of the Service Library by posing LP queries to the Inference engine. The Service Library exposes functionalities to translate requests into suitable queries, evaluate them by means of the underlining engine, and collect the results.

As discussed in the section “Semantic Services”, semantic resources are represented as generic RDF statements of the form *t*(*s*,*p*,*o*). This kind of encoding allows the PIKR to deal indifferently with RDF, RDFS and OWL (restricted to the RL profile). The manipulation and persistence of OWL/RDF files is based on the Jena2 toolkit[10], a well-known OWL/RDF management tool. The PIKR Reasoner implements functionalities to populate, update and query the Inference Engine. At the start-up, it loads into the Inference Engine the logic programs, discussed in the previous section, which enable the reasoning facilities. Then, to perform a specific reasoning tasks, it is responsible for the retrieval of the data from the Triple Store to be used for feeding the inference engine.

The Inference Engine integrates the XSB[11] logic programming (Prolog) system through the Interprolog library[12], a Java/Prolog interface. XSB extends conventional Prolog systems with an operational semantics based on tabling, i.e., a mechanism for storing intermediate results and avoiding to prove sub-goals more than once during the evaluation of logic programs. Tabled evaluation overcomes the three major limitations of Prolog, namely, weak termination, redundancy of computations, and weak semantics for negation. Moreover, for queries falling

[10] http://incubator.apache.org/jena/index.html
[11]The XSB Logic Programming System. Version 3.3, http://xsb.sourceforge.net
[12]http://www.declarativa.com/interprolog

within the stratified Datalog fragment of LP, it guarantee a correct and complete evaluation with the optimal data complexity (i.e., polynomial time). These are crucial motivations for the adoption of XSB as an LP engine for the PIKR Reasoner, because most of the reasoning tasks provided by the reasoned can be encoded as Datalog programs.

GUI Widgets

PIKR GUI module provides interfaces to actors of the VIF for the use of PIKR facilities, each of which is accessible through a GUI widget intended to be used within the VIF Front-end. For the implementation of the presentation functionalities, we are currently adopting Semantic Media Wiki Plus[13] (SMW+), a mature implementation of semantic content management system. SMW+, providing a solid infrastructure for building upon a wiki powerful and flexible "collaborative knowledge-bases". Indeed, it can be seamlessly connected to a Triple Store (in particular, Jena2 is fully supported) thus encompassing user-friendly environments for presenting and collecting both human-readable and machine-processable contents.

The Ontology Building GUI widget provides a number of tools for the definition and maintenance of the I-PIKR ontologies, e.g., adding a new constraint or business rule. The Semantic Annotation GUI widget provides support for annotating, in terms of I-PIKR ontologies, resources to be included into the PIKR knowledge base. Several interaction modalities are implemented, according to the type of resource to be annotated and the corresponding representation in the KROs. The Reasoning GUI widget makes available a number of wizards to assist the user in the formulation of a request to be fulfilled by the services implemented in the Service Library, and in the presentation of the collected results. The Resource Browsing GUI widget presents to the user the content of the semantic descriptors stored in the Triple Store.

[13]http://www.smwplus.com

Semantic descriptors are rendered as wiki-pages, which can be navigated through the semantic relations defined between descriptors, just like traditional Web browsers allow users to navigate through HTML pages by following hypertext links.

Conclusions

In this paper we presented a semantics-based infrastructure, called PIKR, aimed at supporting innovation related activities in a virtual enterprise context, by enabling knowledge classification and sharing, as well as interoperability among participating enterprises.

The PIKR has been designed by following the user requirements and the reference framework produced in the context of the BIVEE European project activities. From a technical point of view the infrastructure is designed according to the Linked Data principles, describing knowledge resources and their semantic relations in terms of a federation of reference ontologies, and providing entry-points to process the maintained knowledge according to well known standards (e.g., RDF/OWL, SPARQL) and technologies (e.g., Web Services). While the actual knowledge resources (e.g., processes, documents, performance indicators) are stored at the premises of the respective owner companies in the virtual enterprise, the PIKR maintains resource images in the form of semantic descriptors that can be regarded as instances of the concepts defined in the ontologies. On top of these descriptions, a set of core semantic services is offered to ease the navigation and retrieval of resources, along with a set of facilities for reasoning over them, intended as a baseline for the development of additional services for populating and exploiting the PIKR.

At the present state of implementation, our semantics-based infrastructure results expressive enough to cover a variety of information needs by people in charge of managing innovation. A more extensive evaluation will be carried out with the collection of actual data about activities, as well as the application of the proposed solution to real world pilot cases. This is the object of ongoing work inside the BIVEE project.

Further work is also planned to extend and refine the methodologies and tools for the building and maintenance of the PIKR ontologies. In particular, the environment for developing the DocOnto will be characterized by a customization approach for allowing each VIF to personalize the structure of the Semantic Descriptors. In this respect, we are working on the integration of the eDoCreator[14], a tool supporting the UBL standard. The adherence to the UBL approach will allow us to promote an initiative aimed at contributing to the UBL standard itself, currently focused on e-procurement documents, by proposing innovation-related document structures.

Finally, we are working on the enhancement of the PIKR towards the direction of an effective support to the management of knowledge in an "open innovation" setting. On the one hand, the adherence to Semantic Web standards and to the Linked Data paradigm allows the linkage of the PIKR to other machine-processable pieces of knowledge available on the Web (e.g., DBpedia[15]), as well as the publishing of the PIKR contents via standard vocabularies (e.g., SKOS, FOAF[16]) to make it accessible from other semantics-aware applications. On the other hand, we are investigating semantic social networking and crowdsourcing techniques, for enabling the participation of the largest number of players in the process of continuous innovation by fostering the cooperation and the human-oriented management of information and knowledge (e.g., through a semantics-based open collaborative whiteboard). These techniques

[14] http://www.srdc.com.tr/home/index.php?option=com_content&view=article&id=90&Itemid=84

[15] http://dbpedia.org/About

[16] http://www.foaf-project.org/

will support socialization activities in the context of knowledge creation, in order to ease the externalization of implicit knowledge into explicit form.

Acknowledgements

This work has been partly funded by the European Commission through the ICT Project BIVEE: Business Innovation and Virtual Enterprise Environment (No. FoFICT-2011.7.3-285746). The authors wish to acknowledge the Commission for its support. We also wish to acknowledge our gratitude and appreciation to all BIVEE project partners for their contribution during the development of various ideas and concepts presented in this paper.

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