

# PaaS Sport Semantic Model: An Ontology for a Platform-as-a-Service Semantically Interoperable Marketplace

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## Abstract

PaaS is a Cloud computing service that provides a computing platform to develop, run, and manage applications without the complexity of infrastructure maintenance. SMEs are reluctant to enter the growing PaaS market due to the possibility of being locked in to a certain platform, mostly provided by the market's giants. The PaaS Sport Marketplace aims to avoid the provider lock-in problem by allowing Platform provider SMEs to roll out semantically interoperable PaaS offerings and Software SMEs to deploy or migrate their applications on the best-matching offering, through a thin, non-intrusive Cloud broker. In this paper, we present the PaaS Sport semantic model, namely an OWL ontology, extension of the DUL ontology. The ontology is used for semantically representing a) PaaS offering capabilities and b) requirements of applications to be deployed. The ontology has been designed to optimally support a semantic matchmaking and ranking algorithm that recommends the best-matching PaaS offering to the application developer. The DUL ontology offers seamless extensibility, since both PaaS Characteristics and parameters are defined as classes; therefore, extending the ontology with new characteristics and parameters requires the addition of new specialized subclasses of the already existing classes, which is less complicated than adding ontology properties. The PaaS Sport ontology is evaluated through verification tools, competency questions, human experts, application tasks and query performance tests.

**Keywords:** Cloud computing; Platform-as-a-Service; Cloud Marketplace; Semantic Interoperability; Ontologies; Quality and metrics

## 1 Introduction

*Platform-as-a-Service (PaaS)* is a Cloud computing service model, where a provider company provides a computing platform allowing customers to develop, run, and manage web applications created using programming languages, libraries, services, and tools, typically supported by the PaaS provider [49]. The consumer of the PaaS does not manage or control the underlying cloud infrastructure including network, servers, operating systems, or storage, but has control over the deployed applications and possibly configuration settings for the application-hosting environment. Compared to the *Infrastructure-as-a-Service (IaaS)* model, where the consumer has control over operating systems, storage, and might have limited control of select networking components, in the PaaS model the provider takes care of the complexity of building, configuring and maintaining the infrastructure layer, whereas the developer worries only about developing, testing and deploying an application on the provided platform. Finally, compared to the *Software-as-a-Service (SaaS)* model, where the provider's application is running on a cloud infrastructure and the consumer can just run them over the web, possibly with limited user-specific application configuration settings capability, in the PaaS model the provider has full control over the application's lifecycle.

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There are many market reports ([10], [15], [74]) indicating that PaaS has a very positive economic outlook for the Cloud market, with an expected growth rate higher than the whole Cloud market, as well as the IaaS and SaaS markets. PaaS, due to its service model, allows for low capital investment. It enables the deployment of applications without the need for provisioning hosting capabilities. It, thus, helps save on the cost incurred for buying and managing the underlying hardware and software. The PaaS model minimizes the incremental cost required for scaling the system with growth in the service usage, while allowing for resource sharing, reuse, life-cycle management, and automated deployment. For these benefits, PaaS is preferred over other solutions for application and service development.

Although giant vendors occupy this emerging space as de-facto standards, including Microsoft, Amazon, Google, and Salesforce.com, many small-medium companies try to enter the PaaS market, not without important inhibiting factors. The battle for dominance in the market between the big vendors makes them reluctant to agree on widely accepted standards promoting their own, mutually incompatible Cloud standards and formats [26]. This dominance increases the lock-in of customers in a single Cloud platform, preventing the portability of data or software created by them. However, even if in theory application and/or data portability is supported, the high complexity and in most cases the additional switching costs discourage users from doing so [3]. The high effort required for exporting application and data from a Cloud platform discourages start-ups and SMEs from entering and bestirring in the flourishing Cloud market [64]. Of course, vendor lock-in is ubiquitous in the computer market, but since the Cloud technology and market are still shaping, there is still a chance to avoid it.

Cloud specialists argue that in the future the leading enterprise software vendors and the large Cloud providers will introduce new PaaS offerings, while both large and small Cloud PaaS providers will grow through partnerships [31]. The formation of partnerships and federations between heterogeneous Cloud PaaS providers involves interoperability. The Cloud community and the European Commission [22] have realized the significance of interoperability and have initiated several approaches to tackle this issue. The first efforts to explore interoperability in PaaS are also well on track, e.g. CAMP (Cloud Application Management for Platforms) [12]. Several studies indicate that Cloud community should:

- promote common standards and interoperability of public Cloud systems, to maximize economies of scale across the globe and create the preconditions for portability between Cloud vendors;
- create the pre-conditions so that the principle of data access and portability between Cloud vendors is widely accepted and the risk of lock-in of users in proprietary systems is prevented.

To lower the barriers that prevent the small-medium Cloud PaaS vendors and software companies from entering the PaaS market, the latter should be able to choose between different Cloud PaaS offerings, offered by the former, and should also be able to deploy their applications easily and transparently between Cloud providers whenever needed. For example, application developers can select either the most reliable platform, or the most well reputed one, or the most cost-efficient one, or simply the one that best meets the technical requirements of their services and applications [6]. Furthermore, application users could decide to switch between platforms, when an SLA (Service Level Agreement) is breached or when the cost is too high, without setting data and applications at risk, e.g. loss of data or inability to run the application on a different platform.

An open market of interoperable Cloud platforms will facilitate small-medium Cloud providers to enter the market and strengthen their position [25]. Furthermore, when interoperability problems have been resolved small-medium Cloud vendors could cooperate through new business models (e.g. in the form of coalitions) to cope with demand fluctuations. For example, an unexpected increase in processing power capacity could force Cloud providers to cooperate to overcome the problem of limited resources. Otherwise, SMEs would seem unreliable to provide the negotiated QoS (Quality of Service), leading consumers to rely on big players for hosting their services and data [31]. Notice, however, that this is only a visionary aspect of our work and it is outside the scope of this paper.

### *1.1 Scope of the paper*

With the above problem formulation in mind, the PaaSport project [58] aims to resolve application and data portability issues that exist in the Cloud PaaS market through a flexible and efficient deployment and migration approach. These include, but are not limited to image conversion to be suitable for

target hypervisor, compression to aid, speed of transfer, image encryption, secure protocols, QoS guarantees, trust issues and cost sharing models. To this end, PaaSport combines Cloud PaaS technologies with lightweight semantics, in order to:

- specify and deliver a thin, non-intrusive Cloud broker (in the form of a Cloud PaaS Marketplace),
- implement the enabling tools and technologies, and
- deploy fully operational prototypes and large-scale demonstrators.

As already discussed, PaaSport’s scope is to enable:

- Cloud vendors (in particular SMEs) to roll out semantically interoperable PaaS offerings, improving their outreach to potential customers, particularly the software industry.
- Software SMEs to seamlessly deploy business applications on the best-matching Cloud PaaS and/or migrate these applications on demand.

PaaSport contributes to aligning and interconnecting heterogeneous PaaS offerings, overcoming the vendor lock-in problem and lowering switching costs. Note that even if “giant vendors” are not our primary target group, since it would be unlikely for them to cooperate with a cloud broker that could potentially cause them to lose clients and, thus, register their offerings in our marketplace, we do support “giant vendors”, such as Amazon, Microsoft, etc. at the technical level, to ease deployment / migration of our client applications between clouds of “giant” vendors and smaller vendors. In this case, our marketplace clients should make a separate agreement with e.g. Amazon, provide us with their keys for the platform, and then our system would just use the clouds public API to provide our brokering services. Thus, our solution can be applied to multiple business use cases; not only SMEs.

In order the above to be realized, the PaaSport project has, among others, a) developed an open, generic, thin *Cloud broker architecture* for an interoperable PaaS offerings marketplace, b) defined a unified *semantic model* for PaaS offerings and business applications, c) developed a unified *PaaS API* (Application Programming Interface) that allows the deployment and migration of business applications transparently to the developer and independent of the specificities of a PaaS offering, d) implemented a *marketplace infrastructure* for semantically–interconnected PaaS offerings, e) defined a unified *service-level agreement model* addressing the complex characteristics and dynamic environment of the Cloud PaaS marketplace, f) defined a Cloud PaaS offerings discovery, short-listing and *recommendation algorithm* for providing the user with the best-matching PaaS offering, and g) delivered a set of PaaS *marketplace utilities* and user-centric *front-ends*. In this paper, we briefly present the *broker architecture* (a) and we report on the unified *semantic model* (b) in detail. Furthermore, we also present how the semantic model has been integrated into the *persistence layer* of the PaaSport *marketplace infrastructure* (d).

Specifically, in order to support the PaaSport marketplace, a unified semantic model has been defined, in the form of an OWL ontology, for representing the necessary characteristics and attributes for the definition of the capabilities of PaaS offerings, the requirements of the business applications to be deployed through the proposed Cloud Marketplace, and the SLAs to be established between offering providers and application owners. The PaaSport ontology has been defined as an extension of the DOLCE+DnS Ultralite (DUL) ontology [29]. This offers extensibility, since both PaaS Characteristics and parameters are defined as classes, so extending the ontology with new characteristics and parameters requires just to add new classes as subclasses of the already existing ones, which is less complicated than adding new ontology properties. This extensibility advantage reflects also on the persistence layer of the PaaSport marketplace, which is built using a relational database. The relational database of PaaSport can be easily extended, as the semantic model evolves, without the need to change existing tables; only new ones need to be added. Finally, the fact that PaaS Characteristics and parameters are represented as first-class objects allows the semantic matchmaking and ranking algorithm, developed for providing the application developer with the best-matching Cloud PaaS offering, to be extensible because it is agnostic to specific PaaS Characteristics and parameters. Notice that the recommendation algorithm has been thoroughly presented in [5].

In the rest of this paper, we review related work in Section 2 on existing ontologies for Cloud computing. We then briefly present the PaaSport marketplace in Section 3, including its architecture, the requirements, use cases, and functionality relevant to the PaaSport semantic models. In Section 4 we present in detail the semantic models. Section 5 evaluates the PaaSport Semantic Model by presenting the verification of the ontology, human and application-based validation and the evaluation of SPARQL query performance comparing to alternative semantic models. Finally, Section 6 concludes the paper with a discussion on future work.

## 2 Related Work

Up until now, there is relevant research on semantically representing Cloud services, which focused on partial aspects of Cloud computing relevant to PaaS. However, no major breakthroughs have yet been reported in the field of discovering Cloud services and performing the matchmaking with the developers' functional requirements. This matchmaking process would further need to establish a defined minimum SLA among the offering provider and the SMEs. In the following, we briefly examine and present the most relevant work on semantic models relevant to the work performed within PaaS.

Androcec et al. (2012) [2] surveyed Cloud Computing ontologies, according to type and applications and focused on four (4) categories of Cloud computing ontologies according to specific scopes:

- *Cloud resources and services description*: Ontologies in this category describe Cloud resources and services, classify the current services and pricing models or define new types of Cloud services. Representative examples belonging to this category can be found in [81], [80], [23], [19] and [1].
- *Cloud security*, namely, models that describe and/or improve security in Cloud environments, such as [71], [47].
- *Cloud interoperability* that deals with how to use ontologies for achieving interoperability among different Cloud providers and their services. Representative examples include [51], [36] and [1].
- *Cloud services discovery and selection*: This category includes the use of ontologies for discovering and selecting the best Cloud service alternative. The most characteristic of the numerous related approaches are [46], [11], [18], [35], and [78], while one of the most innovative ones is presented in [66]. The system architecture of the latter involves (a) a semantic annotation module that encapsulates domain ontologies, (b) a semantic indexing module utilized for discovery purposes, and, (c) a semantic search engine that is exposed to end-users. Using keyword-based search queries, matching and retrieval of identified Cloud services is performed.

Since Cloud computing evolved out of Grid computing, earlier works on using semantics for Grid computing can be considered relevant. For example, the "AiG Grid Ontology" in the context of the "Agents in the Grid Project" [20] defines semantic models of computing resources in the context of Grid Computing. This ontology was applied for automated contracting of computing resources using agent-based negotiations [79]. Ontology concepts were used for describing requirements and constraints in agent contracts.

Another related work paradigm, *OpenCrowd's Cloud Taxonomy* [53], focuses on the latter of the four categories above. More specifically, the Cloud Taxonomy is an online, freely navigable taxonomy that categorizes Cloud Services according to both their service model (IaaS, PaaS or SaaS) and application context. It enables users to discover and access Cloud services so that they can further navigate to respective home pages. Moving beyond just a static model, the Cloud Taxonomy is interactive, where users can contribute comments and recommend additional products to include, aiming at encouraging the dialog between Cloud computing services vendors and developers.

In [21], a unified taxonomy for IaaS and an IaaS architectural framework are presented. The taxonomy is structured around seven layers: core service, support, value-added services, control, management, security and resource abstraction. The authors also introduce an IaaS architectural framework that relies on the unified taxonomy, describing the layers in detail and defining dependencies between the layers and components. The resource characteristics of the PaaS model bare some resemblances with the resource abstraction layer of [21]. However, since PaaS's semantic model focus is on PaaS, there are a lot of differences.

Kourtisis et al. [42] focus on semantic-based QoS management and monitoring for cloud-based systems and proposes a new framework that combines semantic technologies and distributed datastream processing techniques. Among the discussion of challenges and future directions, they mention that a proper semantic-based architecture for cloud computing should contain adequate definitions of functional and non-functional properties, as well as different cloud perspectives (technical vs. business). The PaaS Semantic Model properly addresses the above on the PaaS Parameter and Characteristics level (see section 4.3.4).

Dastjerdi et al. [18] described a framework that facilitates the discovery of Cloud services (IaaS). End-users can register their requirements through a web portal including software, hardware & interfaces description. Using Open Virtualization Format (OVF), the corresponding disk images are generated. The description of users' requirements is expressed in a semantically annotated format (WSML,

Web Service Modeling Language), in order to discover the most appropriate IaaS provided through a matchmaking process. Finally, an SLA is established and a 3rd-party SLA manager component is responsible to monitor and verify respective compliance. The matching module consists of the ontologies and a matchmaking algorithm. Two main ontologies are utilized through the process, namely the requirements ontology and the virtual unit ontology. The former ontology captures the requestor's virtual unit requirements, which are defined as functional properties (e.g., number of CPUs, memory size) and non-functional properties (e.g., budget, location) that represent QoS requirements. Virtual unit ontology provides an abstract model for describing virtual units and their capabilities to let IaaS providers advertise their services.

Tsai et al. [75] emphasize on migrating cloud applications between cloud platforms. A Service Oriented Cloud Computing Architecture (SOCCA) is proposed where cloud computing resources are componentized, standardized and combined in order to build a "cross-platform virtual computer". An ontology mapping layer is configured over these services as a means of masking the differences between cloud providers. Cloud brokers interact with the ontology mapping layer for deploying applications in one cloud or another depending on a series of parameters, such as the budget, SLAs and QoS requirements that are negotiated with each provider. SOCCA applications can be developed using the standard interfaces provided by the architecture or the platform unique APIs of a cloud provider. Compared to PaaSPort, SOCCA uses the ontology as an abstraction level for different cloud APIs rather than service discovery and selection.

*SMICloud* [32] is a framework trying to meet similar requirements to PaaSPort, not taking into account though semantic similarities between different cloud providers and concepts. It is based on the Service Measurement Index (SMI) identified by the Cloud Service Measurement Index Consortium (CSMIC) [13] and proposes SMICloud, a framework that can compare different Cloud providers based on user requirements. A vital step is the Analytical Hierarchical Process (AHP), based on which the ranking mechanism is required to solve the problem of assigning weights to features considering the interdependence between them, thus providing a quantitative basis for ranking Cloud services. The SMI framework provides a holistic view for selecting a Cloud service provider based on accountability, agility, assurance of service, cost, performance, security, privacy and usability. The SMICloud framework provides features such as service selection based on QoS requirements and ranking of services based on previous user experiences and performance of services. Overall, Cloud computing services are evaluated based on qualitative and quantitative Key Performance Indicators (KPIs), i.e. service response time, interoperability, etc. Finally, the ranking system computes the relative ranking values of various Cloud services. The ranking system takes into account two parameters before deciding where to lease Cloud resources from: (a) the service quality ranking based on AHP, and, (b) the final ranking based on the cost and quality ranking.

Various European research projects deal with issues related to using semantics for PaaS portability and interoperability. The *Cloud4SOA* [14] project focuses on resolving interoperability and portability issues existing in current Cloud infrastructures and on introducing a user-centric approach for applications which are built upon and deployed using Cloud resources. Cloud4SOA semantically interconnects heterogeneous PaaS offerings across different Cloud providers that share the same technology. The design of the Cloud4SOA consists of a set of interlinked collaborating software components and models to provide developers and platform providers with a number of core capabilities: matchmaking, management, monitoring and migration of applications. Cloud4SOA focuses on resolving the semantic incompatibilities raised both within the same as well as across different Cloud PaaS systems and enable Cloud-based application development, deployment and migration across heterogeneous PaaS offerings. Cloud4SOA combines three complementary computing paradigms: Cloud computing, Service Oriented Architectures (SOA) and lightweight semantics. The Cloud4SOA Semantic Model consists of five tiers, covering the entire spectrum of fundamental Cloud entities and their relations: infrastructure (IaaS), platform (PaaS), application (SaaS), user and enterprise.

In this work, we have used the Cloud4SOA ontology [39] as the basic knowledge source for capturing the necessary concepts, entities and relationships for Cloud computing, focusing mainly on the PaaS layer and secondarily on the IaaS and SaaS layers (see section 4.1). As already discussed in the introductory section, the focus of PaaSPort is to build a PaaS offerings marketplace where application developers would be able to select the platform offering that best matches the application requirements; thus, the focus of the PaaSPort semantic models also lies in this direction, i.e. how to best serve semantic

matchmaking and ranking of offerings. The Cloud4SOA ontology has made fixed assumptions about the characteristics and parameters needed for matching an application to an offering, and furthermore, had not represented at all how the values of parameters are compared between a request and an offering. For example, when a requirement states that the offering's network latency should be 5ms, it means 5 or less, whereas memory capacity 2GB means at least 2. The Cloud4SOA ontology represents and tests all these requirements as exact matches, whereas in PaaS ontology we are able to represent various range matches, including the ability to describe various units, using the Measurement Unit Ontology (MUO) ontology<sup>1</sup>. To do so, we have combined concepts of the Cloud4SOA ontology with the upper ontology DUL [29] in order to provide a seamlessly extensible semantic model able to describe any current and future parameter for PaaS without the need to reconstruct the core modeling structures of the ontology and the matchmaking algorithms. Finally, in PaaS we are able to check compliance of PaaS offering to application request parameters in a generic and systematic manner, without mentioning explicitly the PaaS characteristics and parameters involved, and to seamlessly extend the ontology concerning future PaaS characteristics and parameters.

The *mOSAIC* project [50] aimed at creating, promoting and exploiting an open-source Cloud application programming interface and a platform targeted for developing multi-Cloud oriented applications. An additional key goal was to ensure transparent and simple access to heterogeneous Cloud computing resources and to avoid proprietary solutions. Furthermore, it aimed to improve interoperability among existing Cloud solutions, platforms and services, both from the application-developer and the application-user perspectives. Within *mOSAIC*, semantic techniques are used for describing application requirements. The *Semantic Engine* component of *mOSAIC* infers the infrastructural requirements from the application description and produces a vendor agnostic SLA template [60]. The *Semantic Engine* helps users in selecting APIs components and functionalities needed for building new Cloud applications as well as in identifying the proper Cloud resources to be consumed. It introduces a new level of abstraction over the Cloud APIs, by providing semantic based representation of functionalities and resources, related by properties and constraints. Using the *Semantic Engine*, the developer of Cloud applications can semantically describe and annotate the developed components, specify application domain related concepts and application patterns. The *mOSAIC*'s Cloud ontology [24] (developed in OWL) describes services and their wrapped interfaces and consists of 15 different base classes. It is built upon existing standards and proposals analysis through annotation of documents and it is used in the *mOSAIC*'s semantic processing. It has been populated with instances of Cloud provider APIs and services specific terms. The underlying platform provides utilities in order to facilitate interoperability among different Cloud services, portability of the developed services on different platforms, intelligent discovery of services, service composition and management of SLAs. Compared to *mOSAIC*, the PaaS ontology is more high-level, and less domain-dependent, aiming only to application deployment / migration needs across cloud platforms and not on application development on (possibly multiple) platforms as *mOSAIC*. Furthermore, PaaS semantic matchmaking is more tolerant towards different cloud platforms and application requirements, because it is domain agnostic.

*REMICS* [63] and *ARTIST* [4] are two projects focusing on the migration of legacy systems (e.g. banking applications written in Cobol) to the Cloud. *REMICS* focusses on the technical migration of such applications. It applies model-driven techniques to recover the legacy system into UML models, and then transforms these UML models into SOA models that can be deployed in a Cloud setting, and continuously evolved later on. *ARTIST* reuses some of the *REMICS* results and additionally focusses on the business aspect of the migration, i.e. how to also modernize the business models of SME and companies migrating to the Cloud. The main use of semantics in these two projects is to identify semantic differences between behavioral semantic model specifications in order to manage software evolution [43]. *REMICS* focuses on model-driven interoperability to facilitate the replacement of a migrated service with another service in case of service failure and recovery. However, in *REMICS*, the decision related to the replacement of a service by another one is fully left to the designer while PaaS uses the Recommendation layer to recommend replacement. However, notice that there is another big difference between *REMICS* and PaaS; *REMICS* deals with behavioral semantics of all services / components of an application, whereas PaaS deals with the semantics of the computing platform on

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<sup>1</sup> <http://idi.fundacionctic.org/muo/>

which the application will run and cares only on capacity features of the offered services, such as resources (quality, quantity), performance, and functionality (e.g. database systems, programming language version compatibilities, etc).

The MODAClouds project<sup>2</sup> uses a Model-Driven Engineering approach for Clouds for semi-automatic code deployment using decision support systems on multiple Cloud providers hiding the proprietary technology stack. Target environments for the MODAClouds framework cover IaaS, PaaS and SaaS solutions spanning across all abstraction layers, supporting public, private and hybrid Clouds. MODAClouds targets Cloud application developers and administrators while PaaSport targets Software DevOps Engineers and PaaS providers. However, both projects aim at delivering methods for the platform-neutral description of cloud services, as well as capabilities for the run-time monitoring. The decision support aspects of MODAClouds are based on a recommendation system that provides the end user with an overview of cloud services from multiple providers meeting their requirements, being somehow similar to the recommendation layer of PaaSport. The matchmaking technique used in MODAClouds [34] is quite different from that of PaaSport, based on the risk assessment method of [45], whereas PaaSport is based on a multi-criteria approach [5]. Both systems end up with a shortlist of recommended services; the difference being that PaaSport is aimed towards a single cloud provider, whereas MODAClouds can end up with multiple vendors for different services. Furthermore, MODAClouds, unlike PaaSport, does not embrace semantic technologies at all. Other earlier projects that shared similar to PaaSport goals for avoiding cloud vendor lock-problems and cloud management based on abstract models are Contrail [9] and VISION Cloud [40], respectively. They also do not involve semantic technologies as PaaSport does.

Regarding PaaS interoperability, there are two main OASIS<sup>3</sup> standardization efforts in progress, Cloud Application Management for Platforms (CAMP) and Topology and Orchestration Specification for Cloud Applications (TOSCA), aimed at an interoperable protocol for cloud providers. CAMP [12] aims at defining the *interoperability* standard of managing applications in PaaS environments. The CAMP approach aims to define in a metamodel the artefacts and APIs that need to be offered by a PaaS cloud for managing the building, running, administration, monitoring and patching of applications in the cloud. The PaaSport ontology has been aligned with the CAMP metamodel, through a CAMP-OWL ontology presented in detail in [56]. Details of this alignment are outside the scope of this paper. On the other hand, TOSCA [72] tries to enhance the *portability* of cloud applications and services. TOSCA provides a standard language to describe the topology of cloud based services, components, relationships and the processes that manage them as well as the operational behavior of these services (e.g., deploy, patch, shutdown). TOSCA defines a meta-model for the structure of a service and how to manage the service. The TOSCA notion of software dependencies between application requirements and service capabilities has been used for the PaaSport offering and application semantic models.

### 3 The PaaSport Marketplace

The PaaSport project focuses on resolving cloud platform interoperability and cloud application portability issues that exist in the Cloud PaaS market through a flexible and efficient deployment and migration approach. To this end, PaaSport combines Cloud PaaS technologies with lightweight semantics in order to specify and deliver a thin, non-intrusive Cloud broker (in the form of a Cloud PaaS Marketplace), to implement the enabling tools and technologies, and to deploy fully operational prototypes.

PaaSport aims to enable Cloud vendors to roll out semantically interoperable PaaS offerings leveraging their competitive advantage and the quality of service delivered to their customers, making their offerings more appealing and improving their outreach to potential customers. PaaSport also aims to facilitate Software SMEs to deploy business applications on the best-matching Cloud PaaS and to seamlessly migrate these applications on demand. Therefore, PaaSport aims to aligning and interconnecting heterogeneous PaaS offerings, overcoming the vendor lock-in problem and lowering switching costs.

In the following subsections, we first discuss the stakeholders and requirements and, then, some use cases that are most relevant to the scope of this paper, namely the use of semantics in the PaaSport Marketplace. Next, we present the architecture of the PaaSport Marketplace infrastructure and, finally, we detail on the functionality of the semantic models in PaaSport.

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<sup>2</sup> <http://www.modaclouds.eu>

<sup>3</sup> <https://www.oasis-open.org>



### 3.1 Semantic Model Requirements

This subsection describes the stakeholders and requirements that drove the development of the PaaS semantic models. These stakeholders had been identified in PaaS project deliverable D1.1 [54]. The stakeholders involved in semantic modelling are as follows:

- **DevOps engineer:** A solution architect seeking an optimal PaaS platform to develop, deploy at, or migrate to, a complex Cloud application. From the viewpoint of the semantic models, the most important optimization criteria for the search and decision-making process are the technical requirements for (or the capabilities of) the platform, regarding both services and resources offered, as well as the SLAs, i.e. the Quality-of-Service (QoS) characteristics of the platform and its services.
- **PaaS provider:** An enterprise whose business model includes the delivery and operation of one or more PaaS solutions. A PaaS provider defines the technical aspects, the pricing models, reference values for quality of service parameters, and terms and conditions that apply to their offerings.
- **PaaS broker administrator:** An individual assigned to the operation, maintenance, and management of the PaaS Cloud broker and marketplace system.
- **Service (or PaaS) consumer:** An individual or an enterprise who uses the application (deployed by the DevOps engineer) on the platform offering. Service consumers are usually concerned only with SLAs, i.e. how the application is delivered through the platform.

PaaS providers supply the DevOps engineers with the available PaaS offerings. The DevOps engineers build applications that will be deployed and executed on PaaS offerings (platform services). The DevOps engineers search for PaaS offerings that satisfy their applications' requirements. After a successful negotiation with a PaaS provider, the DevOps engineer deploys the applications on the PaaS offering, whereas the service (or PaaS) consumer uses the application on the PaaS offering. An application can vary from a simple service, such as a relational database management system or a lightweight Web application, to a heavy software system, e.g. an ERP or a CRM.

**Table 1.** PaaS functional requirements relevant to the Semantic Models.

Stakeholder	Functional Requirements Description	Semantic Models
DevOps engineer	Enable transparent migration of data/applications (portability).	– Application – Offering
DevOps engineer	Be able to manage instances across multiple Cloud providers.	All
DevOps engineer	Enable use of metadata in the declaration of PaaS providers and during matchmaking.	All
DevOps engineer	Support PaaS offerings with elasticity features.	All
DevOps engineer	Be able to search for PaaS services that are held.	– Application – Offering
DevOps engineer	Be able to support a marketplace (application selling business model, SLA adaptation and support, service billing policy).	All
DevOps engineer	Be able to support self-service provisioning and management.	– Application
DevOps engineer	Be able to get recommendations in selecting a Cloud provider based on a hybrid recommender system approach.	All
DevOps engineer	Be able to set the geographic region in which an application is deployed.	All
PaaS provider	Be able to publish service offerings in a service catalogue (service characteristics, policies, application platform availability and performance)	– Offering – SLA
PaaS provider	Manage the SLA contracts	– SLA

**Table 2.** PaaS non-functional requirements relevant to the Semantic Models.

Non-functional Requirements Description
Supporting abstraction (hide many details of system and application infrastructure from developers and their applications).
Uniform service description (SLA offering), using standard formats.
SLAs with clear policies and guidelines for maintenance and version management of the platform and policies for version compatibility for APIs between the platform and the application.



**Table 3.** Requirements that involve the PaaS Semantic Models.

Ontological Requirements Description	Requirement Type	Fulfilment
The ontology should be semantically interoperable or interoperable-ready with similar ontologies	Interoperability	By using an upper ontology (DOLCE+DnS Ultralite) we facilitate semantic interoperability at the conceptual level.
The ontology should be interoperable with industry standard models of Cloud platforms and applications.	Interoperability	In PaaS project deliverable D1.3 [56] we describe how the ontology is aligned with the CAMP meta-model [12]. Furthermore, the TOSCA notion of software dependencies between application requirements and service capabilities has been used for the PaaS offering and application semantic models.
Characteristics and properties of the ontology should be general enough to cover any platform offering and Cloud application.	Usability (Extensibility)	We have studied several Cloud platform offerings for identifying common features (Section 4.1). We have used the Cloud4SOA ontology [39] as inspiration. The PaaS semantic model is the union of all offerings models.
The semantic models should be extensible and modular. It should be easy to add new characteristics and properties, without requiring the adaptation of existing ones.	Usability (Extensibility)	The DUL upper-ontology that was used to build the PaaS ontologies ensures extensibility and modularity since it represents offering parameters detached from the characteristics they characterize (Section 4.2).
The ontology should support efficient and scalable reasoning and processing with regard to the recommendation algorithm of offerings.	Efficiency - Scalability	In [5] we describe that the recommendation algorithm has linear complexity to the number of instances and parameters. Similarly, in Section 5.2 we show experimentally how ontology querying scales-up linearly. In Section 4.3.7, we discuss ontology expressivity and reasoning/querying complexity.
The ontology should interoperate with other system components, especially with the Persistence Storage of the PaaS platform.	Usability (Operability)	The Persistence layer of PaaS uses a relational database which is mapped to the RDF data model using the D2RQ platform [5]. In this way data is kept at a single place (no need for DB synchronization).
The ontology should support the representation of concepts relevant to the PaaS domain, e.g. semantic representation of offerings and applications for the purposes of recommendation.	Usability (Understandability)	We use a core ontological model for characteristics and parameters that affect all the semantic models (offerings, application, SLA models). In this way matchmaking and selection can be performed both syntactically and semantically, in a straightforward manner.

Table 1 shows the most important functional requirements of the PaaS Marketplace that affect also the Semantic Models. In particular, we show the specific sub-model each requirement involves, namely Offering, Application or SLA. Furthermore, **Table 2** presents the most important non-functional requirements of the PaaS Marketplace relevant to the Semantic Models that have to do mostly with the issue of interoperability. Finally, **Table 3** presents requirements related to the Semantic Models / Ontologies themselves, as well as the recommendation algorithm. These requirements have been identified by analyzing the functionality of the Semantic Models in the PaaS project.

### 3.2 PaaS Uses Cases relevant to the use of the Semantic Models

The PaaS use cases [55] most relevant to the use of semantics are the following:

- Manage semantic profile of application
- Search PaaS offering
- Manage PaaS offering

For the sake of space, here we will only present a fusion of the first two use cases. Let a DevOps engineer initiate a search for appropriate PaaS offerings that meet the functional and non-functional requirements that his/her company's application imposes on the platform, in order to select one of the offerings to deploy the application. The course of actions carried out by the system and the user (DevOps engineer) are shown in **Listing 1**.

**Listing 1.** Steps for searching for a PaaS offering that satisfies the requirements of an application.

1. The DevOps engineer initiates the search for PaaS offerings.
2. The PaaSport marketplace displays two options to the user, a semantic search based on an application semantic profile and a search based on a syntactic matching of manually entered search criteria.
3. The DevOps engineer chooses the semantic search option.
4. The system presents the user with a list of all application semantic profiles that have been created by the user.
  - 4.1. The user cannot find an appropriate semantic application profile, so he/she decides to create a new one.
    - 4.1.1. The system creates an empty semantic profile and presents a form to the user that allows him to edit the semantic description of his application.
    - 4.1.2. The user fills the form with the semantic description of his application requirements (functional and non-functional) and finally stores it.
    - 4.1.3. The system successfully validates the entries of the user and stores the application semantic profile. After storing, it presents an option to the user that allows him to initiate a search for a suitable PaaS offering based on the created profile.
    - 4.1.4. The system continues with step 4.
5. The user selects the application semantic profile to be used as search criteria.
6. The system identifies the PaaS offerings that match the search criteria (functional application requirements).
7. For each PaaS offering that matches the search criteria, the system instantiates and presents SLA offers.
8. The system presents a list of all matching PaaS offerings together with the corresponding SLA offer to the user. The list is ordered according to the user's preferences (non-functional application requirements).
9. The user selects the PaaS offering from the list that better meets his/her requirements.
  - 9.1. The DevOps engineer selects a PaaS offering from the list and initiates the process of viewing the detailed description of the PaaS provider to inform himself about the provider's information such as pricing and offering ratings.
  - 9.2. The system loads and presents the detailed description of the selected PaaS provider. It embeds pricing and rating information about the provider and the PaaS offering.
  - 9.3. The DevOps engineer is unconvinced of the PaaS offering due to i.e. bad ratings or provider statistics.
  - 9.4. The user repeats step 9 until he finds a suitable PaaS offering.
10. The user initiates the application deployment process on the selected platform at step 9.

From the above use case, the following competency questions [33] can be derived that will be later used to evaluate the ontology coverage for the intended application domain of the PaaSport platform:

- Step 4: *Find all the application semantic profiles (application requests) for a certain user.*
- Step 6: *Find all PaaS offerings that match functional application requirements.*
- Step 7: *Instantiate an SLA offer for a certain PaaS offering.*
- Step 8: *Score and Rank PaaS offerings using non-functional application requirements.*
- Step 9.2: *Present complete description for a certain PaaS offering and its provider.*

Similar competency questions can be derived from the “Manage PaaS offering” use case, but are omitted due to space limitations.

### 3.3 Architecture of the PaaSport Marketplace Infrastructure

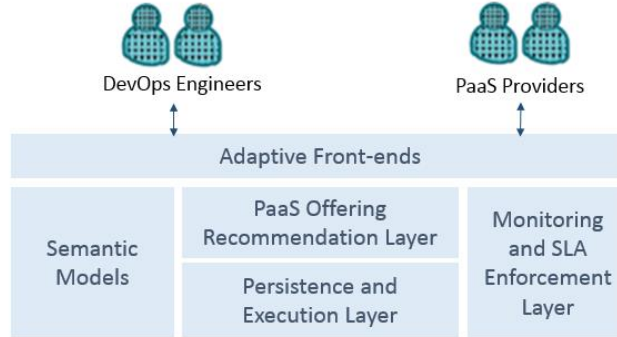
The PaaSport Architecture (**Figure 1**) constitutes a thin, non-intrusive broker and marketplace that mediates between competing or even collaborating PaaS offerings [55]. It relies on open standards and introduces a scalable, reusable, modular, extendable and transferable approach for facilitating the deployment and execution of resource intensive business services on top of semantically enhanced Cloud PaaS offerings.

It comprises of the following five artefacts:

- The Adaptive Front-ends that support seamless interaction between the users and the PaaSport functionalities, through a set of configurable utilities that are adapted to the user's context;
- The PaaSport Semantic Models that serve as the conceptual and modelling pillars of the marketplace infrastructure, for the representation of the registered PaaS offerings and the deployed applications profiles;
- The PaaS Offering Recommendation Layer that implements the core functionalities offered by the PaaSport Marketplace Infrastructure, such as PaaS offering discovery, recommendation and rating;
- The Monitoring and SLA Enforcement Layer that realizes the monitoring of the deployed business applications and the corresponding Service Level agreement;
- The Persistence and Execution Layer that puts in place the technical infrastructure, e.g. repositories, on top of which the PaaSport marketplace is built, including also the PaaSport Unified PaaS API

that is a common API exploited in order to uniformly interact with the heterogeneous PaaS offerings and, in addition, to realize the lifecycle management of the deployed applications.

Our focus in this paper is to present thoroughly the use of semantics in the PaaSport marketplace, as discussed in the next subsection. Besides the PaaSport Semantics models, the architectural layers that mainly deal with semantics are the Offering Recommendation and the Persistence layers.



**Figure 1.** PaaSport reference architecture artefacts [55].

### 3.4 The Functionality of Semantic Models in the PaaSport Marketplace

The PaaSport Semantic Models constitute the conceptual and modelling backbone of the marketplace infrastructure and they are used in order to provide a semantic representation means for the registered PaaS offerings and the deployed applications profiles. Specifically, the functionalities of the PaaSport Semantic Models in the various modules of the PaaSport platform are the following:

- a) They provide a common vocabulary for the various modules of the system and for aligning the models of different PaaS offerings, thus resolving semantic interoperability conflicts among heterogeneous Cloud PaaS offerings that exploit diverse platform and application models, offered service descriptions, offered resources, Quality of Service, SLA formats, billing policies and other important issues (such as location of service or service certifications); and,
- b) Concerning the PaaSport Offering Recommendation layer, the Semantic Models bridge the gap between business application requirements and PaaS offerings capabilities, thus, facilitating the matchmaking and the identification of the specific PaaS that fulfills the business and technical requirements of a particular application.
- c) Concerning the Persistence layer, the database schema follows exactly the conceptual model of the ontologies, in order to avoid syntactic/semantic mismatch between tables/concepts and attributes/properties when the Offering Recommendation layer retrieves PaaS offerings from the database, based on the Semantic Models.
- d) Concerning the Adaptive Front-ends layer, the UIs for managing application and PaaS offering semantic profiles use concepts, properties and restrictions from the semantic models.
- e) Concerning the Monitoring and SLA Enforcement layer, the SLA model has been considered for defining the PaaSport SLA policy model used by the SLA Enforcement component, while the monitoring system has been designed to support the metrics defined in the semantic SLA model.

The first functionality is achieved by: a) considering and fusing together existing approaches to Cloud computing semantic models, b) studying existing Cloud computing platforms, c) taking into consideration the functional and non-functional user requirements, as identified in the next sub-section, and finally, d) considering well known ontology frameworks so that interoperability with other similar efforts outside the project boundaries can be achieved. These are elaborated in Section 4. The second functionality is achieved by using a common conceptual framework for describing both the platform capabilities and the application requirements, so that application profiles can be matched conceptually, structurally and quantitatively to platform offerings, as elaborated in [5]. The third functionality is achieved by mapping the PaaS Offering profiles stored in the database onto the Semantic Model layer (RDF graph) using a relational-to-ontology mapping tool, namely the D2RQ platform [17] (see also in [5]). The fourth and fifth functionalities are beyond the scope of this paper and their achievement can be found in the deliverables of the PaaSport project [58]. Finally, we notice that the UI ensures that the values entered by the

DevOps engineer to define the application semantic profile (requirements) and by the PaaS provider to semantically represent the PaaS offering are compliant to the PaaS semantic models.

## 4 PaaS Semantic Models

In this section, we describe the development of the PaaS Semantic Models. Initially, we briefly present how we have acquired the knowledge to be modelled and then we analyze our modelling decisions and justify how they adhere to the ontology requirements set in Section 3.1. We finally present how the PaaS ontology has been implemented using the descriptions and situations (DnS) ontology pattern of the DOLCE Ultra Lite (DUL) upper level ontology.

### 4.1 PaaS Domain Models

Before starting Ontology development, we have initially surveyed existing cloud computing platforms and PaaS providers and the respective technical background. We have distinguished several key cloud computing platform manufacturers and providers and we tried to record common software / services<sup>4</sup>, platform QoS and pricing policy (plans) that a cloud computing platform and/or a PaaS offering can provide. Notice that there are two types of PaaS providers. The first type, such as Heroku and Amazon, are based on their own proprietary cloud computing platform in order to deliver a single, public cloud. On the other hand, there are PaaS providers, such as OpenShift and Cloud Foundry, that they offer the cloud computing platform as an open-source software, so that several, both public and private clouds can be built on it. Moreover, these providers also offer their own public cloud, built around on their software, of course. **Table 4** reviews the most important cloud computing platforms and their supported programming languages and services, whereas **Table 5** reviews several key PaaS providers, either of the first or of the second type.

Initially, it was decided to study the OpenShift origins and Cloud Foundry, two of the most popular PaaS platform systems. Cloud Foundry and OpenShift are quite similar in their capabilities and their approach to PaaS. While the terminology they use and the exact deployment methods differ, in essence they are very similar: Each delivers a platform based on the Linux OS with lightweight containers that can run applications against open source languages and frameworks, using common services (software), such as databases. This gives the possibility to describe general PaaS platform via our ontology.

Notice that in order to cover maximally all the platform-offering models that we have reviewed, the PaaS semantic model is the union of the reviewed offering models, so that no provider can feel left out. This is important for reaching out the providers. In so doing, the PaaS ontology has many detailed PaaS Characteristics and parameters, as presented in Section 4.3. This means that the providers whose offering model will not match the common “super”-model we have created, will leave many of the offering description characteristics and parameters blank. However, this will not affect the usefulness of the ontology during matchmaking, since it is the DevOps engineer’s request that will guide the search for appropriate platform offerings. Only the parameters filled-in by the DevOps engineer with application requirements will be used for matching the offerings, regardless if the offerings have all or less-than-all parameters filled-in with values. For example, if the request looks for a general characteristic, e.g. storage up to 100GB, but not for a specific type of disk type (HDD or SSD), then both offerings with specified disk type and the ones with not such a specification, will be considered.

**Table 4.** Major Cloud Computing Platforms, supported programming languages and services.

Cloud Computing Platforms	Programming Languages	Services
OpenShift Origin	Ruby, Java, Node.js, Python, PHP, Vert.x, Perl	Tomcat (JBoss EWS), Jenkins, PostgreSQL, MySQL, MongoDB
Cloud Foundry	Java, PHP, Python, Play, Node.js, Ruby, Go	MySQL, PostgreSQL, MongoDB
ApacheStratos	Java, PHP	Tomcat, MySQL
HPE Helion Stackato	Clojure, Go, Groovy, Java, Node.js, Perl, PHP, Python, Ruby, Scala	Apache, JBoss, nginx, Tomcat, MySQL, MongoDB, PostgreSQL

<sup>4</sup> Notice that in our terminology the concept “service” is a synonym for “software”. The services offered by a platform are the pre-installed applications (e.g. databases, web servers, etc.) that come along with the cloud platform.

**Table 5.** Key PaaS providers and provided services.

PaaS Provider	Pricing Policy (plans)	SLA	Re-sources	Programming Languages	Services
OpenShift	Free/Bronze/Silver	✓	✓	Ruby, Java, Node.js, Python, PHP, Vert.x, Perl	Tomcat (JBoss EWS), Jenkins, PostgreSQL, MySQL, MongoDB
Heroku <sup>5</sup>	Hobby/Standard/ Premium/Enterprise	✓	✓	Ruby, Java, Node.js, Scala, Clojure, Python, PHP, Perl	MySQL, PostgreSQL, Redis, MongoDB
Cloudbees	Free/Enterprise	✓	✓	Java, Ruby, Node.js, Clojure, PHP, Erlang, Scala	Tomcat, PostgreSQL, MongoDB
AppHarbor	CANOE/CATAMARAN/ YACHT	✓	✓	.NET	MySQL, SQL Server, PostgreSQL, MongoDB
CloudControl	Developer/Startup/ Business/Business+	✓	✓	Java, PHP, Python, Ruby, Node.js	PostgreSQL, MySQL, MongoDB
Pivotal Cloud Foundry	Aggregated memory used by applications per month	✓	✓	Java, PHP, Python, Play, Node.js, Ruby, Go	MySQL, PostgreSQL, MongoDB
Amazon Elastic Beanstalk	Free trial and proportional price after that	✓	✓	Java, .NET, PHP, Node.js, Python, Ruby, Go	Tomcat, for database can install the instance on Amazon cloud
IBM Bluemix	Free for small resources and proportional price after that	✓	✓	Java, JavaScript, Go, PHP, Python, Ruby	Tomcat, MySQL, PostgreSQL, MongoDB
Microsoft Azure	Free and proportional price	✓	✓	.NET, Python, Java, PHP, Node.js, Ruby	PostgreSQL, MySQL, SQL Server, Azure Cosmos DB <sup>6</sup>
Google App Engine	Free and proportional price	✓	✓	Go, Java, Node.js, PHP, Python, Ruby, C#	PostgreSQL, MySQL, Cloud Datastore
Salesforce <sup>7</sup>	Free trial and proportional price after that	✓	✓	Apex (Java-like), Lightning, Visualforce	Work.com, Data.com, Desk.com, Do.com

Furthermore, we have studied the semantic layer of Cloud4SOA [39] and considered many relevant concepts and entities from this project. More specifically, Cloud4SOA’s semantic layer describes some of the entities for a PaaS platform, featuring five distinct layers, each of which describes one separate view of a PaaS platform:

- The **Infrastructure layer** contains definitions for classes used for capturing knowledge related to the infrastructure (hardware and software) utilized by the Platform and Application layers, as well as metrics to measure the values of hardware/software attributes.
- The **Platform layer** contains definitions for classes used for capturing knowledge related to a Cloud-based platform (e.g. supported programming language, offered software/hardware functionalities). The platform is based on the Infrastructure layer in order to operate.
- The **Application layer** contains definitions for classes used for capturing knowledge related to a Cloud-based Application that is developed/deployed/managed in a Cloud Platform.
- The **Enterprise layer** contains definitions for classes used for capturing knowledge related to the enterprises involved in the Cloud (e.g. the PaaS / IaaS providers) and their role in the Cloud.
- The **User layer** contains definitions for classes used for capturing knowledge related to the users of a Cloud4SOA platform, namely the DevOps engineer and the PaaS providers.

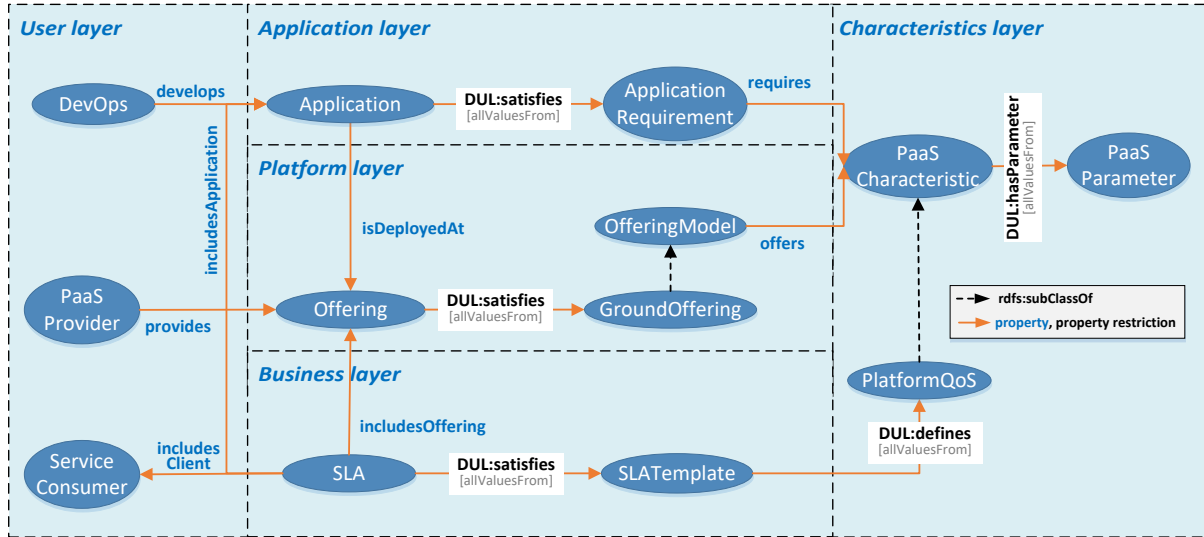
The Infrastructure layer is the basic layer of the Ontology; it provides a common terminology used by the Application and Platform layers enabling the matching between their instances. The Enterprise layer is correlated with the Platform and Infrastructure layers; it defines the enterprises responsible for the offering of Cloud Infrastructure and Cloud Platforms. Finally, the User layer is the topmost layer of the

<sup>5</sup> Owned by Salesforce.com.

<sup>6</sup> NoSQL database with multiple APIs, including MongoDB API.

<sup>7</sup> The Salesforce1 platform is not a general-purpose PaaS since it mainly allows to build applications around the Salesforce.com CRM SaaS.

ontology, it defines the users of the Cloud4SOA platform that are the DevOps engineers (correlated with Application layer) and the Cloud PaaS providers (correlated with Platform layer). It is also correlated with the Enterprise layer since every involved enterprise can have a Cloud4SOA user account. Notice that these layers concern only the semantic representation of the various entities involved in the Cloud and they have nothing to do either with the architecture of the PaaS broker (presented in Section 3) or the stakeholders of the PaaS marketplace (described in Section 3.1).



**Figure 2.** Overview of the PaaS Semantic Model and its layers.

In PaaS, we have followed an almost similar approach concerning the layers (see **Figure 2**, which shows the top-level classes of the PaaS ontology); however, we have mainly focused on concepts and entities from the first three layers (Infrastructure, Platform and Application), giving emphasis on the Infrastructure layer, since the semantic model of PaaS is mainly concerned with semantic match-making between Cloud platform offering capabilities / characteristics and application requirements from the cloud platform [5]. The PaaS semantic models comprise of the following layers:

- **User layer:** contains definitions of classes about the agents (human or corporation) involved in the PaaS marketplace, namely PaaS providers, DevOps engineers and service consumers.
- **Application layer:** contains definitions for classes related to an Application deployment at a Cloud Platform, including the set of application requirements from the platform.
- **Platform layer:** contains definitions for classes related to Cloud computing platforms and platform offerings.
- **Business layer:** contains definitions for classes related to the business aspects of the PaaS marketplace, namely the SLA between marketplace stakeholders and its definition (SLA templates).
- **Characteristics layer:** contains definitions for classes related to the characteristics / capabilities of the platform offerings, namely the infrastructure (hardware and software) utilized by the Platform and Application layers, metrics to measure the values of hardware/software attributes and the platform’s QoS, business characteristics of the platform, such as pricing policy and geographical location of services, user characteristics, such as ratings, etc.

After this research, we combined the knowledge of the real market PaaS providers and the Cloud4SOA ontology<sup>8</sup>, in order to develop an ontology describing all possible components of a PaaS. In addition, we have also used as guides for the development of the PaaS ontology, some of the major standardization efforts for Cloud computing from OASIS, such as CAMP (Cloud Application Management for Platforms) [12] and TOSCA (Topology and Orchestration Specification for Cloud Applications) [72]. Actually, in [56] we have developed an OWL version of the CAMP meta-model and we have aligned it with the PaaS ontology. However, this is beyond the scope of this paper.

<sup>8</sup> [https://github.com/Cloud4SOA/Cloud4SOA/tree/master/semanticModel/C4S\\_model](https://github.com/Cloud4SOA/Cloud4SOA/tree/master/semanticModel/C4S_model)



## 4.2 PaaSport Semantic Modelling Approach

For the development of the PaaSport semantic models, we adopted the NeOn ontological engineering methodology [70]. The main motivation for preferring NeOn over the other methodologies lies on its strong focus on “ontology engineering by reuse”, i.e. reusing existing vocabularies/models (like e.g. Cloud4SOA) when representing domain knowledge. Furthermore, this methodology supports also the reuse of non-ontological resources as part of the engineering process (e.g. the CAMP and TOSCA metamodels in our case). The NeOn methodology also provides detailed guidelines for executing its various activities, including the usage of ontology design patterns as described in chapter “Ontology Design Patterns” [27]. In the PaaSport project, we have decided to develop the PaaSport semantic models<sup>9</sup> (**Figure 2**) as an extension of the DOLCE+DnS Ultralite (DUL) ontology, which is a simplification and an improvement of some parts of DOLCE Lite-Plus library and Descriptions and Situations ontology (see subsection 4.2.1). The main reasons we have followed this approach is the fact that DUL is based on Ontology Design Patterns (ODP) ensuring a high degree of reusability, modularity and extensibility.

The use of DUL (i.e. an upper ontology) ensures better semantic interoperability with other similar projects and research efforts. This is because upper ontologies are supposed to be domain-independent, encompassing very general concepts. Thus, when two ontologies belonging to similar domains are ranked as specializations of the same upper ontology, then most classes of similar meanings belonging to the two different ontologies will be classified under the same general concepts of the common upper ontology. In this way, semantic interoperability is achieved, because even if the two classes are not commonly understood, they could propagate their instances to the common general superclass, thus a minimum level of common understanding is guaranteed. Although not yet a standard, DUL has been used in many projects and offers a very flexible design pattern for defining domain-dependent ontologies.

The DUL ontology is easy to extend by adding e.g. new characteristics and parameters related to PaaSport offerings and applications. Ontologies in RDFS and OWL are generally easy to extend, since new classes and properties can be easily added, without the need to re-configure existing class definitions, since properties are first-class citizens/objects of the ontology. However, the PaaSport semantic model must co-exist and interoperate with the Persistence Storage of the main system. In this case, usually tables correspond to classes and attributes to properties. However, adding a new property to a class roughly corresponds to adding a new attribute to an existing table. This requires schema re-definition. Therefore, extensibility must be exercised very cautiously.

DUL follows a different approach. Properties (i.e. parameters) are defined as new classes and not as OWL properties. In this way, the introduction of new properties/parameters does not require the disturbance of the schema of existing tables, but merely the introduction of new tables. This greatly favors extensibility. Furthermore, this representation of properties also favors the generality and extensibility of the matchmaking / ranking algorithm between application requirements and platform offerings. This type of extensibility has been thoroughly analyzed in [5], but is also discussed in the evaluation (Section 5). In **Table 3** (Section 3.1) we briefly explain how the identified ontological requirements have been fulfilled by the above contributions. Notice that some of the requirements are fulfilled by the recommendation algorithm and the integration of the semantic models into the persistence layer of the PaaSport Marketplace, that has been presented in [5].

### 4.2.1 DOLCE and DnS

The **Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE)** aims at capturing the ontological categories underlying natural language and human common sense. **DnS (Descriptions and Situations)**, is a constructivist ontology that pushes DOLCE’s descriptive stance even further [29]. DnS does not put restrictions on the type of entities and relations that one may want to postulate, either as a domain specification, or as an upper ontology, and it allows for context-sensitive “re-descriptions” of the types and relations postulated by other given ontologies (or ‘ground’ vocabularies).

The current OWL encoding of DnS assumes DOLCE as a ground top-level vocabulary. In fact, the two ontologies combined have been deployed for various modelling purposes devoted to the treatment of social entities, such as e.g. organizations, collectives, plans, norms, and information objects. A lighter OWL axiomatization of DOLCE and DnS is available as **DOLCE+DnS-Ultralite (DUL)**<sup>10</sup>. This lighter

<sup>9</sup> The PaaSport ontology can be found at: <http://lpis.csd.auth.gr/ontologies/paasport/paasport.owl>

<sup>10</sup> <http://www.ontologydesignpatterns.org/ont/dul/DUL.owl>



version (see Figure 3) simplifies the names of many classes and properties, adds extensive inline comments, thoroughly aligns to the repository of Content patterns and greatly speeds up consistency checking and classification of OWL domain ontologies that are plugged to it.

The core model of the PaaS ontology has been developed as a specialized instantiation of the DnS design pattern. The DnS pattern provides a principled approach to context reification through a clear separation of states-of-affairs, i.e. a set of assertions, and their interpretation based on a non-physical context, called a “**description**”. Intuitively, DnS axioms try to capture the notion of *situation* as a unitarian entity out of a state of affairs, with the unity criterion being provided by a *description*. In that way, when a description is applied to a state of affairs, a situation emerges. The core-modeling pattern of DnS allows the representation of the following conceptualisations, as illustrated in Figure 3:

- **Situations.** A situation defines a set of domain entities that are involved in a specific pattern instantiation (*isSettingFor* property) and they are interpreted on the basis of a *description* (through *satisfies* property). Each situation is also correlated with one user/agent (*includesAgent* property).
- **Descriptions.** An activity description serves as the descriptive context of a situation, defining the concepts (“defines” property) that classify the domain entities of a specific pattern instantiation, creating views on situations.
- **Concepts.** The DUL concepts classify domain entities describing the way they should be interpreted in a particular situation. Each concept may refer to one or more parameters, allowing the enrichment of concepts with additional descriptive context.

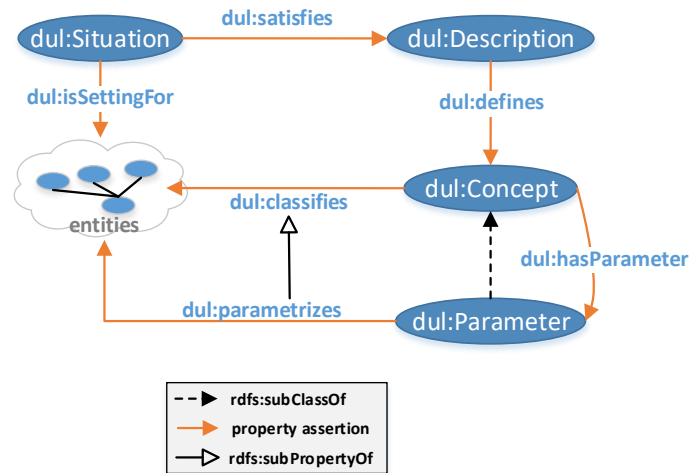


Figure 3. DUL overview.

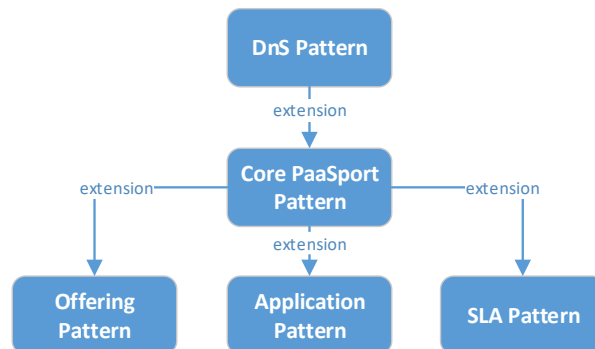


Figure 4. DnS pattern.

As we describe in subsection 4.3, the PaaS semantic models have been defined as extensions to the core DnS pattern (Figure 4). More specifically, the situation concept is used as a container for defining the higher-level conceptualizations of the PaaS domain, such as PaaS offerings, application deployments and SLAs. Offerings are considered as situations, since they represent (possibly different) “views” of a cloud platform, related to (possibly different) provider(s). The SLA is a relational situation

between a provider and a client, involving an application that is deployed on a platform offering. Finally, applications are situations as well, since in PaaS semantic models they actually denote application deployments on a specific platform that may change in the future, and not the application code itself, which might endure.

The specialized situations are further correlated with specializations of the description concept, allowing the correlation of the situations with additional descriptive context (Figure 5). The descriptions in turn define one or more concepts with appropriate domain parameters, resulting in a rich, dynamic and flexible modelling pattern able to address the domain modelling requirements identified so far.

### 4.3 The PaaS Ontology

In the following, we describe the core modelling patterns we have developed that serve as the conceptual bases for modelling PaaS-related concepts. The proposed patterns implement the DnS ontology pattern of DOLCE Ultra Lite (DUL) ontology that provides a formal modelling basis and has been used for a number of core ontologies (e.g. Semantic Sensor Network – SSN ontology [16], Event-Model-F [67], Temporal Abstractions [65], Emotions [44], Activity Patterns [48], etc.), none of them related to cloud computing so far, while the pattern-oriented approach of DUL provides native support for modularization and extension by domain specific ontologies. Actually, the “Offering Pattern” is represented through the combination of the OfferingModel and GroundOffering classes, the “Application Pattern” is represented by the ApplicationRequirement class, and finally, the SLA Pattern is represented by the SLATemplate class.

Figure 5 displays the associations between DUL and the PaaS semantic models. Applications, Offerings and SLAa are PaaS situations (subclass of SUL situation), which satisfy the corresponding PaaS descriptions, namely Application Requirement, Ground Offering and SLA Template. PaaS Characteristics specialize DUL concepts and are defined in PaaS descriptions. The “defines” property is specialized as “requires” for application requirements and as “offers” for PaaS offerings. SLA templates define only platform QoS parameters, aggregated as a PlatformQoS characteristic.

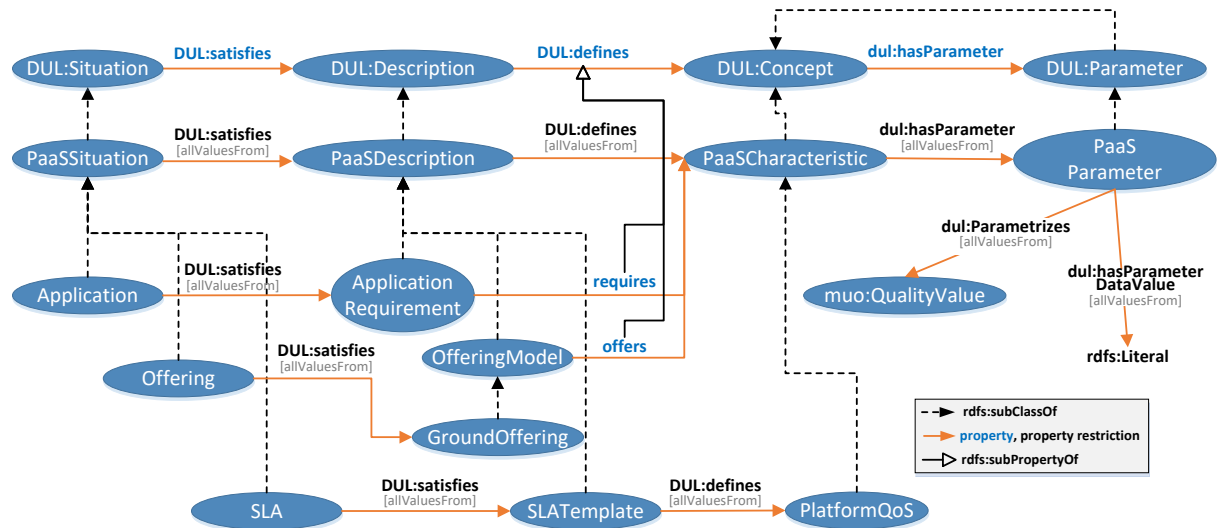


Figure 5. Overview of DUL and PaaS associations.

The extensibility of the PaaS semantic model depends on the parameters’ definition. A situation (offering, application, SLA agreement) can have a set of characteristics (description). A characteristic (for example PlatformQoS) can have one or more parameters. Every parameter has a value (dul:hasParameterDataValue) and a “quality” (dul:parametrizes), which is the “physical” or “logical” dimension of the parameter (e.g. storage, duration, etc.) and it is usually (not always) accompanied by measurement units. For this reason, if we know the quality of the value we can easily compare two parameters and by extension two characteristics. If we want to add a new parameter to a characteristic, we have only to declare the quality value of this parameter. Moreover, we could do the same for characteristics, i.e. we

can just add a new characteristic to the corresponding description. Furthermore, if we want new characteristic and parameter types, we just add new classes in the corresponding hierarchies, without the need to redefine any ontology properties, since the “requires”, “offers” and “hasParameter” properties cover all (sub)classes of PaaS Characteristics and Parameters.

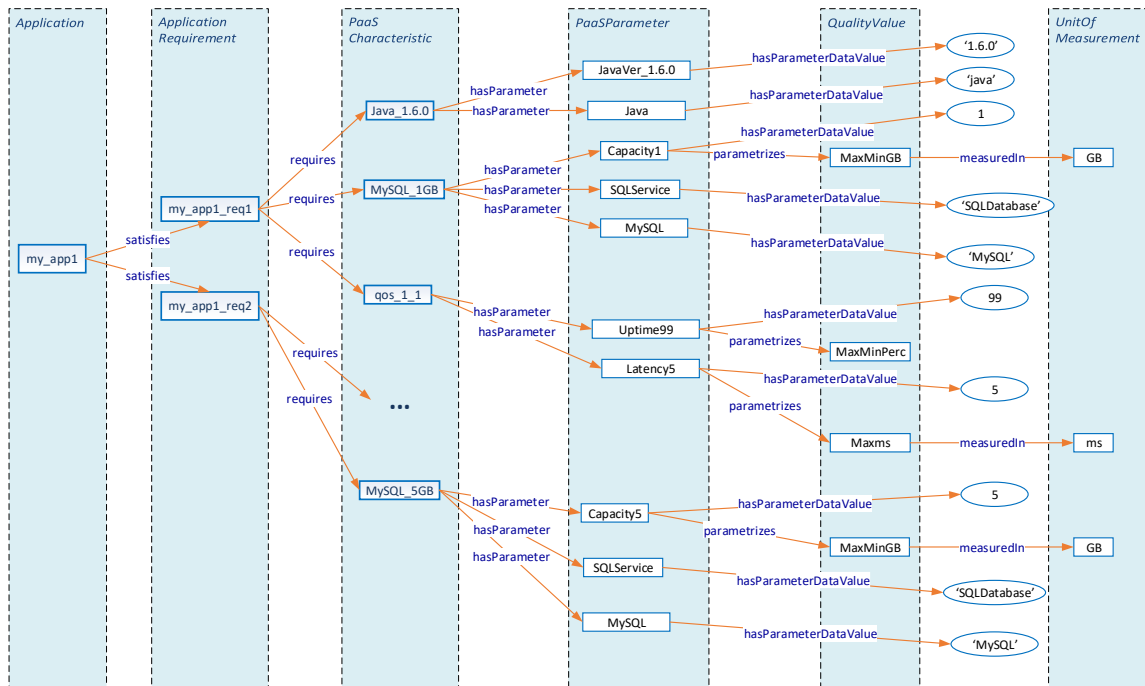


Figure 6. An Application example.

The application example in **Figure 6** describes the logic underlying our proposed model. Specifically, we provide an application which is linked to two different sets of requirements. This is allowed by the PaaSPort Semantic Model and its rationale lies on the fact that there might be different sets of requirements e.g. for minimum, moderate or optimal performance for the same application. The first set of requirements is about the programming language (Java ver. 1.6), the database (MySQL with minimum 1GB size for storage) and the platform’s QoS, with maximum (network) latency 5ms and minimum uptime 99%. So, according to the DUL ontology, an “Application” (my\_app1) “satisfies” an “Application Requirement” (my\_app1\_req1) which consists of a set of PaaS Characteristics that the “Application” “requires”, such as “Programming Language” (Java\_1.6.0), “Services” (MySQL\_1GB), “PlatformQoS” (qos\_1\_1), etc. Each PaaS Characteristic consists of one or more PaaS parameters, such as name or version of the programming language, service type (SQLService), DB capacity (Capacity1), etc. The “PlatformQoS” characteristic has several “QoS Parameters”, such as service uptime (Uptime99), network latency (Latency5), etc. Each parameter is linked to (“parametrizes”) a quality value (MaxMinGB, Maxms) that contains the actual parameter value (hasParameterDataValue) and optionally a measurement unit (e.g. “measuredIn” millisecond, GB, etc). The quality values belong to different types (such as single, min, max, etc.) that define how the application requirement value should be compared to the corresponding offering value (exact match, greater than, less than, etc.). More on this are discussed in section 4.3.5. In **Figure 6**, for example, the platform’s QoS parameter network latency is shown, which belongs to the Max quality value type, meaning that the application requires a maximum acceptable limit 5ms for the network latency. Notice that the PaaSPort semantic model also allows for QoS parameters of individual software/services provided by the infrastructure of the platform through the paas:ResourceParameter class (see Section 4.3.4).

The Offering and Application models are not very different. Only the top-level classes are different, since Offerings and Applications stand conceptually for two very different types of entities: cloud platforms and cloud application deployments, respectively. However, both use the same vocabulary for describing services (PaaS Characteristics) and their parameters, since the restrictions on the dul:defines

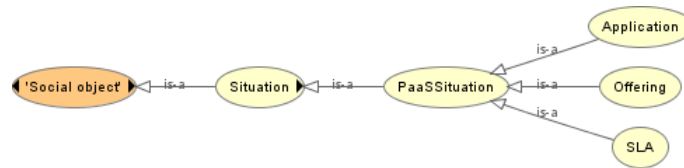
property are inherited by all subclasses of PaaSDescription, as shown in **Figure 5**. This allows the recommendation algorithm to seamlessly match application requirements to PaaS offerings both syntactically and semantically ([5]).

Actually, PaaS semantic models follow the “Requirements and Capabilities” model of TOSCA [72] or the “Requirements and Characteristics” model of CAMP [12], which allow for expressing requirements and capabilities of components of a service or an application. In this way, PaaS semantic models can represent dependencies between components, i.e. when a component depends on (requires) a feature provided by another component, or that a component has certain requirements against the hosting environment such as for the allocation of certain resources. More specifically, the offering model describes the capabilities of the services offered by a certain platform, whereas the application model describes the service, resource or QoS requirements that an application has on the platform, in order to be deployed on it. Since PaaS is concerned with stand-alone PaaS environments, which do not include technical, licensing or financial dependencies on specific SaaS applications or web services, the single-level dependency scheme that the PaaS semantic models offer is adequate. Finally, the SLA model is concerned just with the QoS characteristics of the platform.

In what follows, we first give a brief description of the three PaaS Semantic Models, i.e. Offering, Application and SLA, and then we describe in detail the PaaS Characteristics and parameters, which constitute the core part of the ontology that bridges all the semantic models, through the use of common characteristics and parameters for the platform offering capabilities and the application profile requirements. More details descriptions can be found at [56].

#### 4.3.1 Offering Model

The Offering Model helps PaaS providers semantically describe their PaaS offerings. Specifically, it contains all available capabilities of a PaaS offering and its services. These capabilities are part of the PaaS hierarchy of characteristics (see section 4.3.4) and can be technical, performance-related, geographical etc.



**Figure 7.** PaaS situations hierarchy.

**Figure 7** shows the hierarchy for the Offering class. PaaSSituation is an abstract superclass for all Situation entities of PaaS, namely Offering, Application and SLA (also shown in **Figure 5**). The core entities of the offering model are the PaaS Offering and its description. The Offering class represents (and is related to) a grounded PaaS Offering. The set of the characteristics / capabilities offered by the platform (e.g. services, resources, platform QoS, etc.), can be found by following the “satisfies” property assertions (**Figure 5**). An offering is linked to its provider as well as to its deployed applications (**Figure 2**). Notice that although the word “provides” usually cannot be associated with the word “offering”, but rather with the word “service”, in PaaS semantic model, class “Offering” actually refers to a “PaaS offering”; therefore, it represents a service. We define two classes of the offering description:

- a) The **OfferingModel** represents the description of a cloud computing platform, i.e. a set of software and tools that can be downloaded and installed on a private or a public cloud, e.g. “OpenShift Origin”. The offering model description describes general capabilities of a platform, such as supported programming languages, databases, servers, etc. These capabilities are common in every installation (instantiation) of the PaaS offering model. It is linked through the “offers” property to characteristics describing the capabilities of the offering. Actually, an offering model consists only of the ProgrammingEnvironment and Service characteristics. Characteristics like offered resources and platform QoS are not part of an offering model but of a GroundOffering. In practice, when a user adds a new cloud computing platform in the PaaS marketplace he/she will first create an instance of this class.

- b) The **GroundOffering** represents the description of a grounded PaaS offering and consists of all PaaS capabilities / characteristics, such as programming environment, services, resources, QoS, location, pricing etc. The resource, platform QoS, pricing and location characteristics are defined when an Offering Model becomes a GroundOffering (necessary and sufficient conditions). In practice, when a new PaaS offering is added in the PaaSport marketplace an existing offering model is “grounded” by creating a new instance of the GroundOffering class; all the characteristics of the corresponding model (service and programming environment) will be copied to the new instance and the capabilities of the grounded offering, such as resources, platform QoS, etc., will be added as well. For example, RedHat’s OpenShift<sup>11</sup> is a GroundOffering of the “OpenShift Origin”<sup>12</sup> OfferingModel. There can be several such groundings, especially for open source cloud computing platforms, whereas for several commercial PaaS, such as Heroku<sup>13</sup>, there is only one grounding.

#### 4.3.2 Application Model

The Application Model comprises definitions for classes that capture knowledge related to Cloud-based application requirements or software/resource dependencies on the hosting Cloud platform. We designed a simple, open and extendable vocabulary, which allows the semantic representation of developers’ application requirements. Based on the Application Model and the ontology of PaaS Characteristics and parameters (see section 4.3.4), the DevOps engineer creates and manages the semantic profile of his/her application deployments (**Figure 2**), regarding software, resource or platform QoS dependencies. The developer can define functional (software dependencies on programming language, servers, database, etc.) and non-functional (resource capacities, performance, price, etc.) requirements for his application. Specifically, these requirements refer to the deployment platform and allow developers to match the PaaS Offerings whose capabilities are the most relevant to their application requirements.

The main class is Application, which represents a Cloud-based application deployed at a PaaS Offering. The set of requirements for the Application from the platform can be found by following the “satisfies” property assertions (**Figure 5**). An application is linked to its developer. The ApplicationRequirement class is the description of an Application and consists of a set of application requirements, which are PaaS-related Characteristics that can be modeled using “requires” property assertions. Notice that requirements are complex entities, consisting of many parameters, e.g. a database requirement could be MySQL v. 5.7 with minimum storage capacity 5GB.

Notice that the application requirements are added by the DevOps engineer to describe the requirements that the application has from the cloud computing platform to be deployed at. If the offered platform characteristics are not compatible with (do not “satisfy”) the application requirements, then two things can happen:

- a) If the offered characteristics are less than required (or “buggy”), then the application will run less than optimal (or not run at all). This will result in the dissatisfaction of the client of the application.
- b) If the offered characteristics are more than required, the platform offering will probably cost more. This will result in the dissatisfaction of the client of the application.

Thus, it is in the best interest of the DevOps engineer to report the application requirements truthfully.

#### 4.3.3 SLA Model

SLA (Service Level Agreement) is an agreement between two parties, the Service Consumer (the PaaSport user who deployed an application) and a PaaS Offering Provider. The level of service is formally defined in terms of performance and reliability, through the SLATemplate class, which is a rough schema of the offers the responder is willing to accept, and it also involves the application and the offering. The SLA has a period of validity that is defined in terms of the StartDate and EndDate properties. The performance is described by platform QoS parameters and the pricing by the pricing policy parameters (**Figure 8**), similarly to the platform QoS and pricing parameters of the PaaS Characteristic hierarchy (see section 4.3.4).

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<sup>11</sup> <https://www.openshift.com/>

<sup>12</sup> <https://www.openshift.org/>

<sup>13</sup> <https://www.heroku.com/>



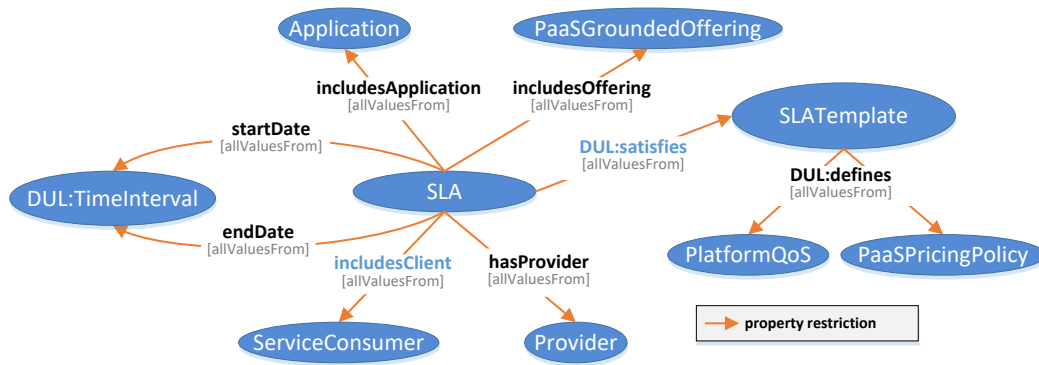


Figure 8. SLA overview.

#### 4.3.4 PaaS Characteristics and Parameters

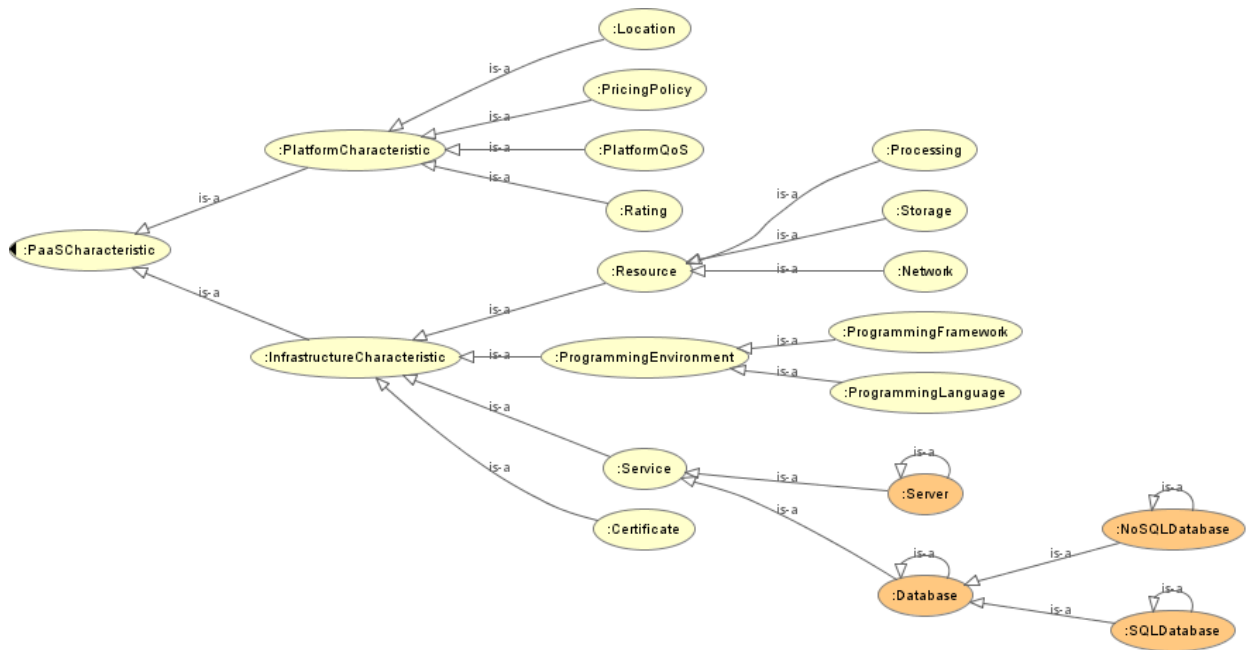
This subsection describes in detail the key notions of core PaaSport ontology classes PaaSCharacteristic and PaaSParameter, which are used by all PaaSport semantic models and bridge the gap between them. In PaaSport, a **PaaSCharacteristic** is a basic unit of a PaaS offering capability or characteristic (or of a cloud application requirement) and represents an abstract concept of a cloud platform feature (e.g. programming language, database, uptime, storage, etc.). For the application developer it represents an application requirement about the deployment platform and for the PaaS provider it is a part of the description of the capabilities / characteristics offered by the platform. For example, in the PaaS offering of **Figure 19**, sample instances of PaaS Characteristics include, Java (v. 1.6), instance of the ProgrammingLanguage class (subclass of PaaSCharacteristic), MySQL, PostgreSQL and MongoDB, instances of the Database class, and platform QoS characteristics, such as latency and uptime.

Each PaaSCharacteristic is associated with one or more PaaSParameters, through the DUL:hasParameter property and can be considered as an aggregator object for related parameters. For example, the MySQL database PaaSCharacteristic might be comprised of parameters concerning the database service name (MySQL), the database type (SQL), the version of MySQL (5.7), the provided storage capacity of the database (e.g. 10GB), etc. Characteristics can be backwards compatible with other characteristics (through the isCompatibleWith property). This is mainly used for characteristics such as versions of offered programming languages or services/software.

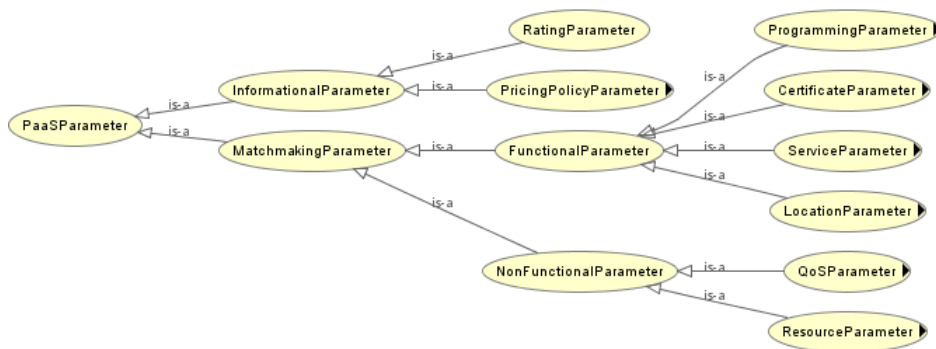
PaaS characteristics are classified into two categories: a) characteristics that deal with the infrastructure needed to deliver the PaaS offering, such as Programming Environment, Service, Resource, and Certificate, and b) characteristics that refer to qualities inhering in a PaaS offering, such as platform QoS, Pricing Policy, Location and Rating. **Figure 9** shows the class hierarchy for PaaS characteristics.

A (PaaS)parameter is a property of a (PaaS)characteristic, enriching it with additional descriptive context. For example, the value “0.09 seconds” refers to the Latency of the provided service. The value of the parameter is defined using the **hasParameterDataValue** property. Through OWL restrictions we associate parameters with specific PaaS characteristics. A PaaSParameter can be either:

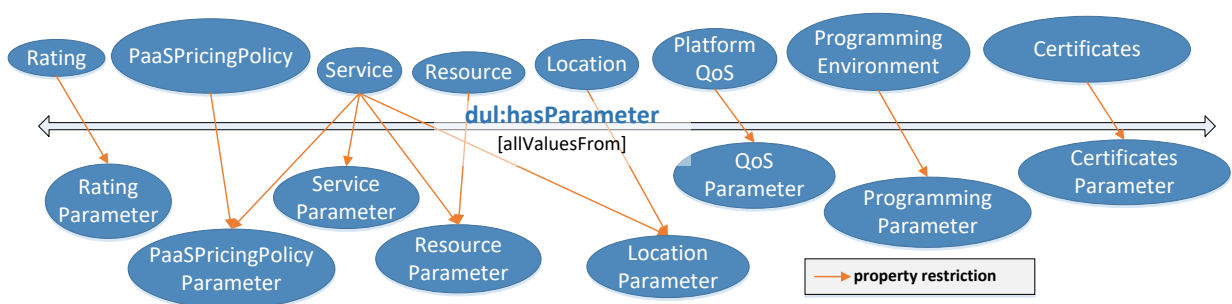
- a **MatchmakingParameter**, i.e. a parameter that participates in matchmaking and ranking, or
- an **InformationalParameter** that is used only for informational reasons and can be inspected manually by the application developer for decision-making or any other purpose.
- Moreover, the matchmaking parameters are divided into functional and non-functional parameters via the **FunctionalParameter** class: when a parameter is a subclass of FunctionalParameter, then it can only be used as a functional requirement, otherwise it can be used both as a functional and a non-functional requirement. Functional requirements are the requirements that, when not met by an offering, then the offering cannot be considered as a candidate for deploying an application. Non-functional parameters usually measure the quality of a service and are used in order to rank the selected services according to the order of preference. Notice that a non-functional parameter can also be used as a functional one if the user wishes to. For example, if “latency less than 10ms” is absolutely required, offerings that do not satisfy this criterion are not considered at all. This can be selected by the user through the user interface. **Figure 10** illustrates the major subclasses of PaaS-Parameter and **Figure 11** gives an overview of the association between characteristics and parameters. In the following, we elaborate on some key PaaS Characteristics and parameters.



**Figure 9.** The PaaS Characteristic hierarchy



**Figure 10.** The PaaS Parameter hierarchy



**Figure 11.** Overview of characteristics and parameters.

**Service** is a piece of software that is part of a platform offering (pre-installed), such as a database server, a web server, or any other software package (not necessarily a server). Services can be related to the location where the servers that provide them are located (especially for cloud databases this is important due to legislation issues), resources (e.g. up to which storage capacity the application can use, either for all its data or just for a single service), and cost (either of the platform as a whole or for a specific service). The service parameters are categorized into four categories (**Figure 12**):

- **ServiceParameter** describes the basic properties of a service, such as name, type, version etc.
- **Cost** refers to pricing policy of the specific service.



- **ResourceParameter** describes the platform resource-related parameters of a service, such as storage capacity, memory capacity, bandwidth etc. Notice that some of these parameters may reflect the QoS for the individual service / software provided by the platform, as opposed to the QoS parameters of the whole Platform-as-a-Service.
- **LocationParameter** describes where the server that provides the service is physically located; for example, a service can be a database server located in Europe.

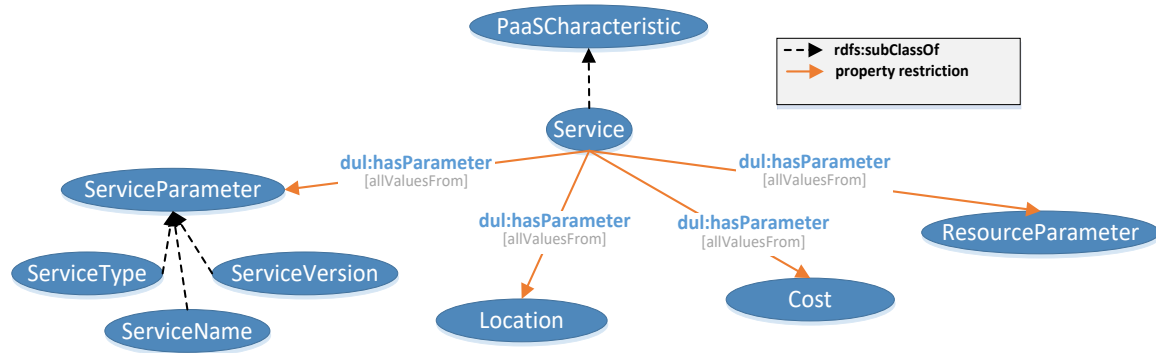


Figure 12. Parameters of a Service.

In addition, the Service class has two subclasses **DB** and **Server** (Figure 9). The DB (SQL, NoSQL) class represents a database service provided by a platform offering and the Server class represents a web server or any other type of server that might be offered by the platform. The subclasses of Service are directly related to instances of the ServiceType class through a necessary and sufficient hasValue restriction. Notice that when a user of the PaaSPort platform needs to add services that are not in the above two categories, then he/she can create a new direct instance of class Service, without any specific type. However, if this service belongs to a service type that is missing from the PaaSPort taxonomy, then only the PaaSPort administrator can evolve the ontology by adding a new subclass of the Service class and the corresponding instances of the ServiceType class. This can only be done offline (e.g. upon platform upgrades) and requires some minor amendments to the ontology, the DB of the persistence layer and the user interface.

An example of a Service (Apache Server 2.2) is presented below:

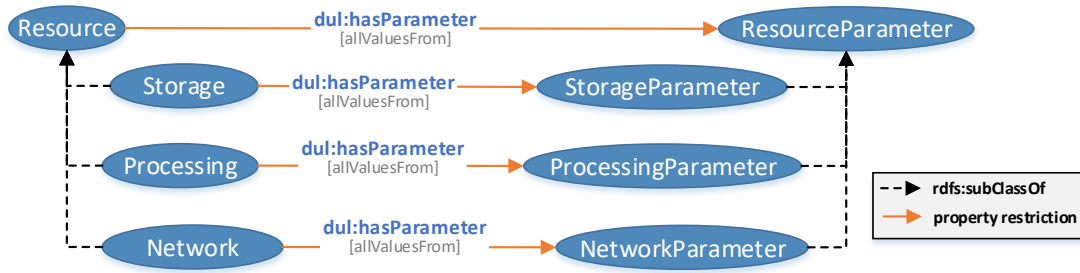
```

<paas:Server rdf:about="&paas;apache_2.2">
  <DUL:hasParameter>
    <paas:ServiceVersion rdf:about="&paas;apacheVersion">
      <DUL:hasParameterDataValue rdf:datatype="&xsd:string">2.2</DUL:hasParameterDataValue>
    </paas:ServiceVersion>
  </DUL:hasParameter>
  <DUL:hasParameter>
    <paas:ServiceName rdf:about="&paas;apacheName">
      <DUL:hasParameterDataValue rdf:datatype="&xsd:string">Apache</DUL:hasParameterDataValue>
    </paas:ServiceName>
  </DUL:hasParameter>
  <DUL:hasParameter rdf:resource="&paas;ServerType"/>
</paas:Server>
  
```

Class **Location** describes the geographical location of a platform or a service of a platform, since it is usual that due to legislation issues, a DevOps engineer may require the whole platform or a service of the platform to be located somewhere specifically. Location is associated with **LocationParameters**. Currently in PaaSPort we support continents and countries. However, this could be refined to smaller granularity if needed. Furthermore, we may link these entities to linked open geographical datasets in the future. Class **Certificate** describes certificates and standards (e.g. involving security) of a platform or certificates/standards required by an application. Certificate is associated with **CertificateParameters**, which can be one of CertificateName, CertificateType, and CertificateVersion.

The **Resource** class describes the hardware-related resources offered by the platform or requested by an application developer, e.g. storage capacity, memory capacity, network bandwidth, etc. Its subclasses are **Storage**, **Network** and **Processing** (Figure 13). The actual resources are specified as resource parameters. In a similar manner, the subclasses of the **ResourceParameter** class are **StorageParameter**

(e.g. disk type, capacity), **ProcessingParameter** (e.g. CPU architecture, number of cores, memory capacity) and **NetworkParameter** (e.g. bandwidth, latency, concurrent connections) (**Figure 14**).



**Figure 13.** Resource and resource parameters.



**Figure 14.** Full Resource Parameters hierarchy.

Notice that usually, in Service Oriented Architecture, services are described logically and independently from their physical realization. In this vein, the connection of a service to resources might seem inappropriate. However, in the PaaS ontology we use the term “service” differently, as already explained, namely as a piece of software offered on a Cloud platform by a PaaS provider to the service (PaaS) consumer. Therefore, each platform offering (according to our market research in section 4.1) has different resource settings according to different plans (pricing policies). For example, a free plan may offer very limited memory/storage capacity, whereas a premium plan would allow larger capacities up to a limit, etc. Therefore, the correlation of platform services/software to resources, in PaaS, is not connected to the physical implementation of the services, but rather to the allowed usage of resources from the deployed application according to the selected pricing policy of the offering.

Furthermore, concerning resources (such as storage) provided as a service, at a first glance it might seem risky to indicate (or dictate) details about how it is provided (e.g. SSD or HDD disk type), since it might limit the ability of the PaaS provider to effectively manage their available resources. However, the PaaS ontology aims to aid PaaS providers to properly describe / advertise their platform capabilities and application developers to accurately express their application requirements (either functional or non-functional / performance-related) in order to effectively select the correct and rank / shortlist the best platform offerings to deploy their application. In this vein, the type of resources, which usually dictate both the expected QoS as well as pricing, is definitely relevant. This allows the developer to choose between quality (but expensive) platform plans or inexpensive (but more common) PaaS offers. One such example can be found at the Heroku platform<sup>14</sup>, where some of the cheaper plans do not include SSD disks for the storage, whereas the more expensive plans do. This indicates that such resource details are important for selecting the appropriate platform offering.

An example of a storage resource (OpenShift free gear Storage) is presented below:

```
<paas:Storage rdf:about="&paas;gearStorage">
  <DUL:hasParameter>
    <paas:StorageCapacity rdf:about="&paas;gearStorageCapacity">
      <DUL:parameterizes rdf:resource="&paas;StorageCapacityGB"/>
      <DUL:hasParameterDataValue rdf:datatype="&xsd;integer">1</DUL:hasParameterDataValue>
    </paas:StorageCapacity>
  </DUL:hasParameter>
</paas:Storage>
```

Class **ProgrammingEnvironment** describes a programming language (e.g. Java, PHP, Python) or a programming language framework (e.g. PHP Zend, Python Django) used for developing Cloud-based applications. The programming framework concept includes complex versioned programming suites, such as Anaconda. Every instance of ProgrammingEnvironment has some parameters, such as language name, language version, framework name, and framework version. These parameters are subclasses of **ProgrammingParameter** (Figure 15).

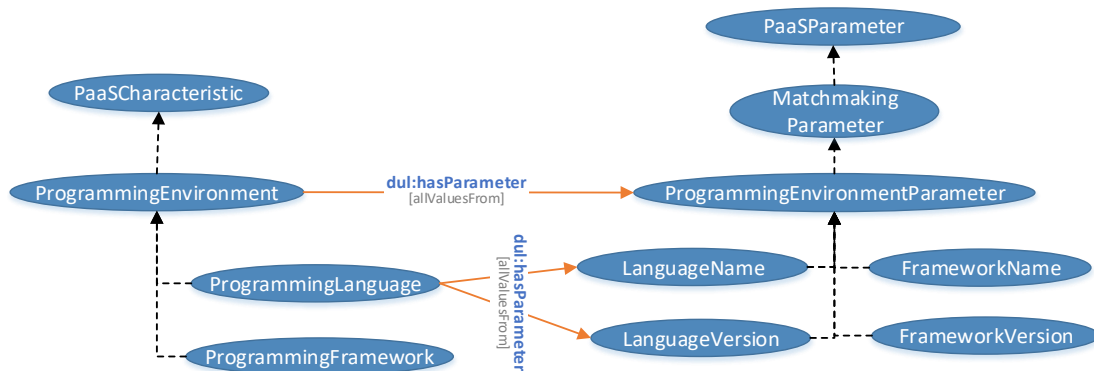


Figure 15. ProgrammingEnvironment and parameters.

An example of the Java programming language (version 1.6.0) is given below:

```
<paas:ProgrammingLanguage rdf:about="&paas;java_1.6.0">
  <DUL:hasParameter>
    <paas:LanguageVersion rdf:about="&paas;javaVersion_1.6.0">
      <DUL:hasParameterDataValue rdf:datatype="&xsd:string">1.6.0</DUL:hasParameterDataValue>
    </paas:LanguageVersion>
  </DUL:hasParameter>
  <DUL:hasParameter>
    <paas:LanguageName rdf:about="&paas;javaName">
      <DUL:hasParameterDataValue rdf:datatype="&xsd:string">Java</DUL:hasParameterDataValue>
    </paas:LanguageName>
  </DUL:hasParameter>
</paas:ProgrammingLanguage>
```

<sup>14</sup> <https://elements.heroku.com/addons/jawsdb>

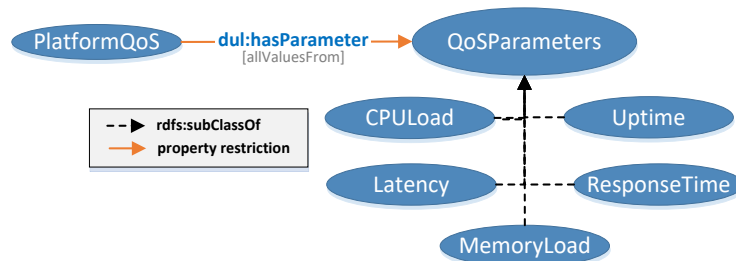
Class **PlatformQoS** represents the platform’s Quality of Service metrics and its parameters are subclasses of QoSParameter. These parameters are MaxCPULoad, MinCPULoad, Latency, MaxMemoryLoad, MinMemoryLoad, ResponseTime and Uptime (**Figure 16**).

**MaxCPULoad** is the upper limit on the percentage of CPU load after which the platform scales up, e.g. “scale up if CPU load is higher than 90%”. Notice that this limit can be interpreted by the application requirement in two ways:

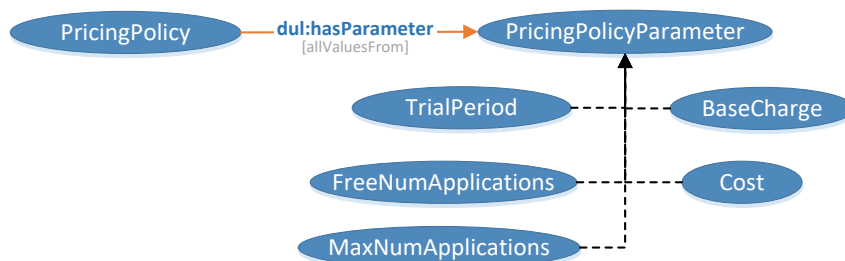
- If the application profile is similar to a server-like application, then the application requirement for this limit is to be as low as possible, in order to be able to handle as many new requests as possible. So the application requirement treats this as a minimum acceptable limit; a “compatible” offering may offer the same-as-requested or an even lower CPU load.
- If the application profile is similar to a data-intensive application, then the application requirement for this limit is to be as high as possible, in order to utilize the CPU as much as possible. So the application requirement treats this as a maximum acceptable limit; a “compatible” offering may offer the same-as-requested or an even higher CPU load.

In order to comply with both the above application profiles, the DUL:parameterizes property is restricted to RangeValue, i.e. the superclass of the Max and Min classes. When the application requirement is defined, the parameter will become an instance of one of the two most specific classes Max and Min. Max is for data-intensive apps, Min is for server-like apps. Exactly the same behavior is met by **MaxMemoryLoad** parameter, which is the upper limit on the percentage of memory load after which the platform scales up.

**MinCPULoad** is the lowest limit on the percentage of CPU load below which the platform scales down, e.g. “scale down when CPU load is below 30%”. Notice that this limit is always interpreted in the same way by the application requirement; it needs to be as high as possible so that the platform will scale-down early enough so that the CPU load is maintained relatively high (e.g. at least 50%). In this way cost is saved (no need to pay for extra VMs when not really needed). Therefore, it is treated as a Min Range Value. Exactly the same behavior is met by **MinMemoryLoad** parameter, which is the lowest limit on the percentage of memory load below which the platform scales down.



**Figure 16.** Platform QoS and parameters.



**Figure 17.** PricingPolicy and parameters.

**Latency** is the maximum *network* latency of an offering (or the *network* maximum latency required by an application). It is the delay incurred due to communications. Furthermore, **ResponseTime** is the time elapsed between sending a request and the reception of the first response, whereas **Uptime** is the percentage of time in a specific period that the application is up and running, or the offering is available.

**PricingPolicy** contains details about the pricing policy of a PaaS offering (as a whole) or of the cost of a specific service offered by a PaaS offering (e.g. database cost) and can take parameters of the type

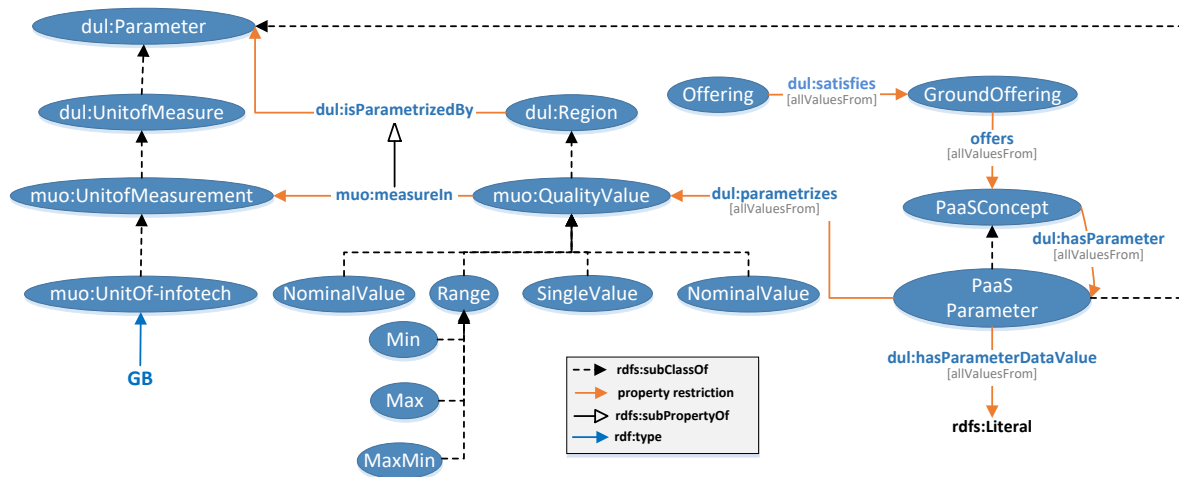
**PricingPolicyParameter.** Some of the pricing policy parameters are base charge of the offering/service, trial period, extra costs for additional services, the number of free applications that a developer can deploy, and the maximum number of instances that a developer can deploy (**Figure 17**). Finally, class **Rating** represents the rating of a PaaS offering; this value is the average of the users’ ratings.

#### 4.3.5 Quality Values and Units

The Measurement Unit Ontology (MUO) has been used for semantically representing the various measurements and units in the PaaS domain. The ontology can be used for modelling physical properties or qualities. Every unit is related to a particular kind of property. For instance, the Hz unit is uniquely related to the frequency property. Under the provided ontological approach, units are abstract spaces used as a reference metrics for quality spaces, such as physical qualia, and they are counted by some number. For instance, weight-units define some quality spaces for the weight-quality where specific weights of objects, like devices or persons, are located by means of comparisons with the proper weight-value of the selected weight-unit.

In MUO, the class `muo:QualityValue` (a specialization of `dul:Region`) is used for representing the values of qualities, for instance, the amount of available memory. Instances of this class are related with: a) exactly one unit, suitable for measuring the physical quality (meters for length, grams for weight, etc), by means of the property `muo:measuredIn` (a specialization of `dul:isParametrizedBy`); b) a number, which expresses the relationship between the value and the unit by means of the `rdf:value` property; and c) a time, which expresses the quality value along the line of time. Quality values can be temporalized, but this is not always necessary. In PaaS, we use MUO to represent the units as well as qualitative attributes, whereas values are represented using the DUL vocabulary (`dul:hasParameterDataValue`).

The reason why we have used the MUO ontology, instead of defining our own units using the DUL class `dul:UnitOfMeasure` is that MUO has a large set of well-known predefined unit instances, derived from “The Unified Code for Units of Measure (UCUM)”<sup>15</sup>. Almost all physical, chemical and IT units are already defined there. However, we had to extend the unit knowledge base with some derived IT units, such as GB or MB, but we have re-used the basic unit (byte).



**Figure 18.** Quality values and units of measurement.

In PaaS (Figure 18), there are a lot of quality values that represent how a value of a PaaS offering parameter can be compared and matched to the corresponding application requirement parameter:

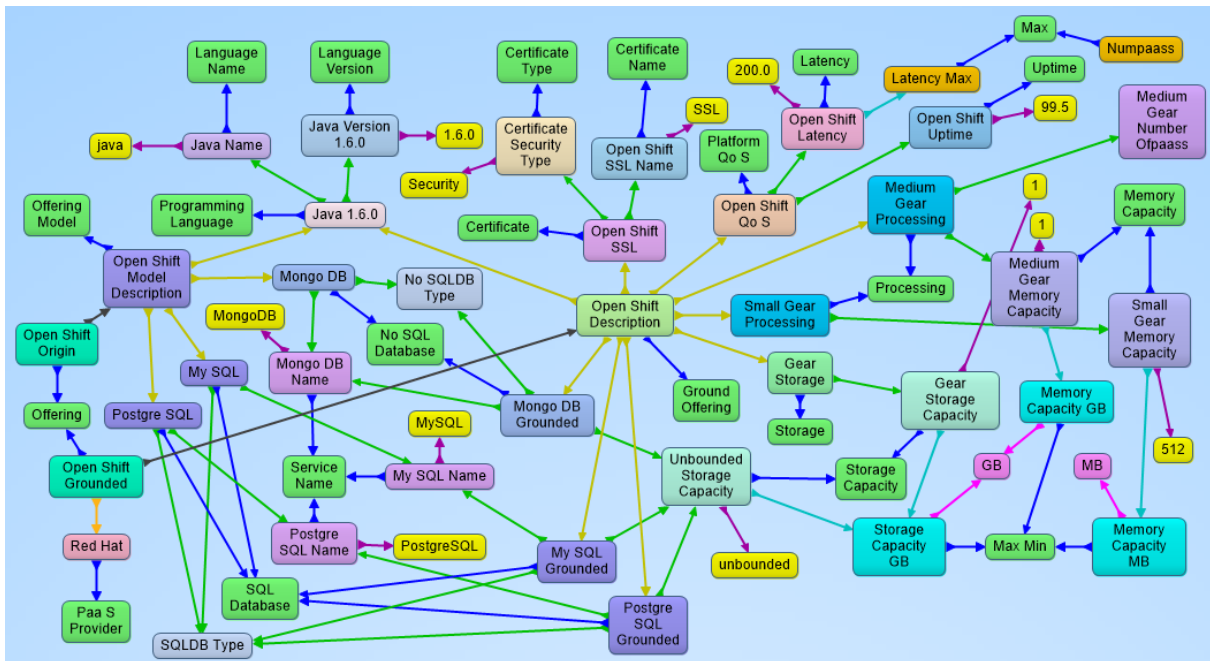
- Single Values, either symbolic or numeric, that require an exact match.
- Nominal Values, which are enumerated data types and require an exact match.
- Ordinal Values, namely ordered enumerated data types, which also require exact match, but order can be established for better or worse.
- Range Values, which are numeric values that require range match, e.g. “less than” or “equal”. There are four subclasses of this class, according to the matchmaking profile of each parameter.

<sup>15</sup> <http://unitsofmeasure.org/trac>

- \* Max: Range Value with a Max upper limit. Matches less than or equal.
- \* Min: Range Value with a Min upper limit. Matches “greater than” or “equal”.
- \* MaxMin: Limit that is Max for Offering and Min for Application. Matches less than or equal.
- \* MinMax: Limit that is Min for Offering and Max for Application. Matches greater than or equal.

#### 4.3.6 Instance Example

In **Figure 19**, we include a complete instantiation example of a PaaS offering, namely OpenShift. There are two major instances involved, the OpenShift Origin PaaS model, and the grounded OpenShift offering from RedHat. The grounded offering includes two different containers (Gears) with small and medium main memory and storage capacities, the Java language (v. 1.6), MySQL, PostgreSQL and MongoDB with unbounded storage capacity, and platform QoS characteristics, such as latency 200 ms and 99.5% uptime. **Table 6** shows the color legend for properties and classes of **Figure 19**.



**Figure 19.** A complete offering example.

**Table 6.** Legend of colors of **Figure 19**.

Properties	Classes		
Has Parameter	Certificate	Max Min	QoS
Has Parameter Data Value	Certificate Name	Memory Capacity	Service Name
Measured In	Certificate Type	No SQL Database	Service Type
Offers	Class	Number Of Cores	Simple Derived Unit
Parametrizes	Ground Offering	Offering	SQL Database
Provided By	Language Name	Offering Model	Storage
Satisfies	Language Version	PaaS Provider	Storage Capacity
Type	Latency	Processing	Uptime
	Max	Programming Language	Literal

#### 4.3.7 Expressivity and Reasoning

The PaaS Semantic Models reuse the conceptual model provided by the DOLCE+DnS Ultralight (DUL) foundational ontology and therefore, they inherit all the modelling properties and expressivity characteristics of the upper-level model. More specifically, the expressivity falls under the  $SHOIN(D)$



description logic, allowing a) atomic negation, i.e. negation of concepts that do not appear on the left-hand side of axioms; b) concept intersection; c) universal restrictions; d) existential quantification; e) complex concept negation; f) inverse properties; g) cardinality restrictions; and h) role transitivity. However, excluding DUL, the expressivity in the PaaSPort ontology alone is  $\mathcal{ALCHOIN}(\mathcal{D})$ , i.e. dropping role transitivity above.

Regarding the computation complexity of reasoning, it strongly depends on the OWL 2 reasoning profile [8] that is used to implement the matchmaking algorithms. An OWL 2 RL (Rule Language) implementation is NP-COMPLETE (or PTIME if only the size of the KB matters), whereas by using an OWL 2 DL (Description Logic) reasoner (under direct semantics), the reasoning complexity increases to N2EXPTIME-complete, supporting though higher expressivity. Similarly, the computational complexity of SPARQL that is used to query the data strongly depends on the language constructs used for defining queries [59]. The full SPARQL (e.g. using FILTER, UNION, OPTIONAL operators) is PSPACE-complete, whereas all OPTIONAL-free graph patterns are either NP-COMPLETE (whenever operator AND co-occurs with UNION or SELECT/CONSTRUCT) or in PTIME.

In the actual implementation of the semantic matchmaking algorithm of PaaSPort [5], Jena and its native rule-based OWL reasoner is used, thus the computation complexity of reasoning is NP-COMPLETE. So is the computational complexity of SPARQL queries used, since UNION (but not OPTIONAL) construct is used, along of course with AND and FILTER (see section 5.2 and [5]).

## 5 Evaluation

In this section, we evaluate the PaaSPort semantic model in several directions. First, we report on the metrics of the Ontology as well as how it was verified for correctness and application domain coverage. Then, we present a human evaluation of the PaaSPort semantic model in scope of the total PaaSPort platform, followed by an application based evaluation. Finally, we evaluate the scalability of the ontology regarding size and query performance and we compare it with the ontology of Cloud4SOA [39].

### 5.1 Ontology Verification and Metrics

The PaaSPort ontology was developed with the TobBraid Composer Free Edition [73] from TopQuadrant. In this subsection, we present the verification methodology we have used for the ontology, as well as some metrics associated with it, which have been provided by a different ontology editor (Protégé [62]). A literature review of ontology metrics reveals a variety of such metrics aiming to assess and qualify an ontology. A good overview of ontology evaluation methods is given in [28] and in [7]. An ontology evaluation process may target different qualitative or quantitative criteria. Such techniques help uncover errors in implementation and inefficiencies regarding the modelling, complexity and size of the ontologies. Nevertheless, none of the evaluation methods, neither alone nor in combination, can guarantee a “good” ontology, but can surely help identify problematic parts [76]. Any given approach may address more or less specific issues; therefore, evaluation methodologies partially clarify the problems at stake [28]. For verifying the PaaSPort ontology, we have selected three evaluation methods, details of which are given in the following: (a) an automated ontology evaluation tool named OOPS!, (b) Protégé metrics, and (c) coverage of competency questions identified in Section 3.2.

OOPS! (Ontology Pitfall Scanner) is a web application [52] that helps detect some of the most common pitfalls when developing ontologies [61]. For example, OOPS! warns you when:

- The domain or range of a relationship is defined as the intersection of two or more classes. This warning could avoid reasoning problems in case those classes could not share instances.
- No naming convention is used in the identifiers of the ontology elements. In this case the maintainability, the accessibility and the clarity of the ontology could be improved.
- A cycle between two classes in the hierarchy is included in the ontology. Detecting this situation could avoid modelling and reasoning problems.

The generated results suggest how the ontology could be modified to improve its quality. Nevertheless, these suggestions should be manually interpreted and revised properly by the knowledge engineer. Three levels of importance have been identified in the evaluation process via OOPS!:

- critical pitfalls, that affect the ontology’s consistency and reasoning,
- important pitfalls, which are not critical, but are important to fix, and



- minor pitfalls, which do not cause any practical problem, but correcting them will make the ontology clearer and more compact.

We have evaluated the PaaS ontology by submitting it to OOPS!. Most of the pitfalls detected concern the imported ontologies, namely DUL and MUO, and they will not be reported here. **Table 7** includes the PaaS ontology’s pitfalls detected by OOPS!, along with a brief description. For missing annotations, the actions are trivial so we do not report them further. For the cases of missing inverse relationships, two of them involved the relationships “requires” and “offers” that relate an application requirement and an offering model to PaaS Characteristics. The inverse relationships “isRequiredBy” and “isOfferedBy” have been introduced as subproperties of the DUL property “isDefinedIn”. The third case involved the isCompatibleWith property between PaaS Characteristics, which was turned into transitive and symmetric instead. Finally, the recursive definition involved the “PaaSCharacteristic” class and the isCompatibleWith property. The recursion was due to the fact that despite class PaaSCharacteristic was the domain and range of the property, we have included also a redundant local range property (allValuesFrom restriction) for this property at class PaaSCharacteristic, restricting it again to PaaSCharacteristic. This restriction was just removed.

**Table 7.** PaaS Ontology’s pitfalls detected by OOPS!

Pitfall	Number of cases
P08: Missing annotations (Minor) Ontology terms lack annotation properties, either rdfs:label or rdfs:comment, that would improve the ontology understanding and usability from a user point of view.	113
P13: Missing inverse relationships (Minor) There are relationships (except for symmetric ones) that do not have an inverse relationship defined within the ontology.	3
P24: Using recursive definition (Important) An ontology element is used in its own definition.	1

Furthermore, we also present the ontology metrics provided by Protégé [62] that are based on the general structure of the ontology and are classified into the following general groups [30]:

- General metrics, such as counters for classes, object/data properties and individuals.
- Class axioms, such as subclass axioms, equivalent class axioms, disjoint class axioms, etc.
- Object property axioms, which include counters for object properties axioms such as total values of sub-object properties, equivalent, inverse, disjoint, functional, transitive, symmetric, antisymmetric, reflexive and irreflexive object properties, as well as counters for data properties domain and range.
- Data property axioms, including datatype properties counters, meaning total values of sub-datatype properties, equivalent, disjoint and functional datatype properties, as well as counters for data properties domain and range.
- Individual axioms, with counters for class assertions and same or different individual axioms.
- Annotation axioms, with counters for annotation assertions and for domain and range annotations.

**Table 8** includes the respective metrics for the PaaS ontology alone or in combination with DUL and MUO ontologies, as provided by the ‘ontology metrics’ view in Protégé, along with some comments. Notice that only non-zero metrics (for the PaaS ontology) are reported. The metrics are not used as a means to evaluate the ontology, but only to give the reader a measure of the ontology. As can be observed, the ontology is quite rich in classes, which are made subclasses of the DUL upper level ontology. Also many new (but fewer) object properties are introduced, as subproperties of DUL properties, meaning that some DUL properties have been re-used. There is only one new datatype property. This is because parameters of the PaaS offerings are not directly represented as datatype properties, but instead they are made first class (reified) objects that actually need only one datatype property (hasParameter-DataValue). This feature of the DnS ontology design property is very useful for the extensibility of the ontology. Specifically, when new features are added, either PaaS Characteristics or characteristic properties, one has to add only new classes as subclasses of already existing classes. The individuals defined in the ontology are instances of the ServiceType class (SQL, NoSQL, etc.) and of the MUO ontology, namely the KB, MB, GB, TB instances for measuring memory / disk capacities. These are all derived units of measurement, derived from ‘byte’. The last row of **Table 8** refers to the DL (Description Logic)

expressivity of the PaaS ontology; DL provides the logical formalism underlying OWL 2. The PaaS ontology has a DL expressivity level of  $\mathcal{SHOIN}(\mathcal{D})$  (see section 4.3.7), therefore it is equivalent to OWL 2 DL. This expressivity is inherited by the DUL ontology. The expressivity of the PaaS ontology alone is  $\mathcal{ALCHOIN}(\mathcal{D})$ .

**Table 8.** PaaS Ontology metrics by Protégé

Metric	Count (excl. DUL)	Count (incl. DUL)	Comment
Axioms	528	3263	<i>Shows a significant extension of DUL (~17%)</i>
Logical axioms	282	2128	
AnnotationAssertion	112	947	
Classes	112	142	<i>A large number of concepts related to the cloud (PaaS) domain</i>
SubClassOf	196	222	
EquivalentClasses	5	5	<i>Needed for sufficient restrictions (classification)</i>
Object properties	33	38	<i>A large number of object properties related to the cloud (PaaS) domain</i>
ObjectPropertyDomain	19	23	
ObjectPropertyRange	17	22	
SubObjectPropertyOf	20	20	<i>Many object properties introduced as specialization of DUL properties</i>
FunctionalObjectProperty	2	5	<i>Start and End date of an SLA</i>
InverseObjectProperties	7	7	<i>Inverse relationships between PaaS stakeholders</i>
Data properties	1	9	<i>Not many data properties were needed</i>
Individuals	8	381	<i>Very few instances (mostly the ontology metrics)</i>
DataPropertyAssertion	8	804	
ClassAssertion	12	736	
DL expressivity	$\mathcal{ALCHOIN}(\mathcal{D})$	$\mathcal{SHOIN}(\mathcal{D})$	

Finally, **Table 9** reports on the coverage of the competency questions related to the most critical use case for PaaS semantic models, that have been identified in Section 3.2. Some questions are handled by the matchmaking and ranking algorithm that has been presented in [5], while the rest are answered using sample SPARQL queries. Notice that the  $\langle Devops \rangle$  placeholder refers to the ID (URI) of a specific DevOps engineer / user of PaaS, whereas  $\langle Offering \rangle$  refers to a registered PaaS offering.

**Table 9.** Ontology evaluation using competency questions.

Competency Question	Answer
Find all the application semantic profiles (application requests) for a certain user.	<pre>SELECT * WHERE {   &lt;Devops&gt; paasport:develops ?Application .   ?Application dul:satisfies ?Requirement .   ?Requirement paasport:requires ?characteristic .   ?characteristic dul:hasParameter ?par .   ?par dul:hasParameterDataValue ?Value .   ?par dul:parametrizes ?qualityVal .   ?qualityVal uomvocab:measuredIn ?Unit . }</pre>
Find all PaaS offerings that match functional application requirements.	Matchmaking algorithm described in [5]. Also see SPARQL queries in Listing 2 and Listing 3.
Instantiate an SLA offer for a certain PaaS offering.	<pre>CONSTRUCT {   ?SLATemplate dul:defines ?characteristic . } WHERE {   ?SLA paas:includesOffering &lt;Offering&gt; .   ?SLA dul:satisfies ?SLATemplate .   &lt;Offering&gt; dul:satisfies ?GroundOffering .   ?GroundOffering paasport:offers ?characteristic .   ?characteristic rdf:type paasport:PlatformQoS . }</pre>

Competency Question	Answer
Score and Rank PaaS offerings using non-functional application requirements.	Matchmaking algorithm described in [5].
Present complete description for a certain PaaS offering and its provider.	<pre> SELECT * WHERE {   &lt;Offering&gt; dul:satisfies ?GroundOffering .   ?GroundOffering paasport:offers ?characteristic .   ?characteristic dul:hasParameter ?par .   ?par dul:hasParameterDataValue ?Value .   ?par dul:parametrizes ?qualityVal .   ?qualityVal uomvocab:measuredIn ?Unit .   ?Provider paasport:provides &lt;Offering&gt; . } </pre>

## 5.2 Evaluation by Humans

During the development of the PaaSport ontology, it has been informally reviewed by human experts which were partners in the project (see Acknowledgments section), on many occasions, i.e. during working technical meetings and hackathons, as well as when reviewing related project deliverables [56]. These comments led to constant ontology improvements towards to fulfill its initial goal, namely to be functionally integrated into the PaaSport platform.

**Table 10.** Results of human evaluation related to semantic models of PaaSport

Stakeholder	Aspect	Question	Max	Min	Avg	SD	Median
PaaS provider	Functionality	Was it easy to manage the semantic annotations of your PaaS offering?	5	3	3,83	0,69	4
PaaS provider	Functionality	Were you able to fully annotate your offer?	5	3	3,81	0,69	4
DevOps engineer	Functionality	Are you satisfied with the semantic search based on an application semantic profile?	4	1	2,90	1,05	3
DevOps engineer	Functionality	How many semantic search requests did you make?	12	3	8,45	3,53	9
DevOps engineer	Usability	Is the feature for semantic annotation easy to use?	5	1	3,21	1,15	3
DevOps engineer	Usability	Is the semantic search functionality simple to use?	5	3	4,07	0,75	4
DevOps engineer	Usability	Is the matching functionality simple to use?	5	1	3,90	1,08	4
DevOps engineer	Reliability	Are the semantic search results reliable?	5	1	3,55	1,30	4
DevOps engineer	Efficiency	How much time did it take to prepare a semantic search?	5	1	3,48	1,30	4

Furthermore, the PaaSport semantic models have been formally evaluated by humans, both PaaS providers and DevOps engineers, during the evaluation of the whole PaaSport platform<sup>16</sup>. The goals of the evaluation were the validation of software and design supporting aspects, including the Semantic Models. Three different business demonstrators are performed during the PaaSport project. The validation in the frame of these demonstrators shows how European SME PaaS providers can benefit from using the PaaSport results. During real-life events (trainings and workshops) the evaluation was measured by inviting intended users of the PaaSport system to participate in a test session. During this test session, a user was given a series of tasks to complete by using PaaSport, without major assistance, just demonstration. The researchers recorded the user's performance as he/she attempts to accomplish each task and distributed a questionnaire (completed in the first phase of the PaaSport project). Respondents were actively involved in the analysis and interpretation of findings. Actually, 12 PaaS providers and 29 DevOps engineers participated in the evaluation. In making questionnaires that use the Likert Scale, not

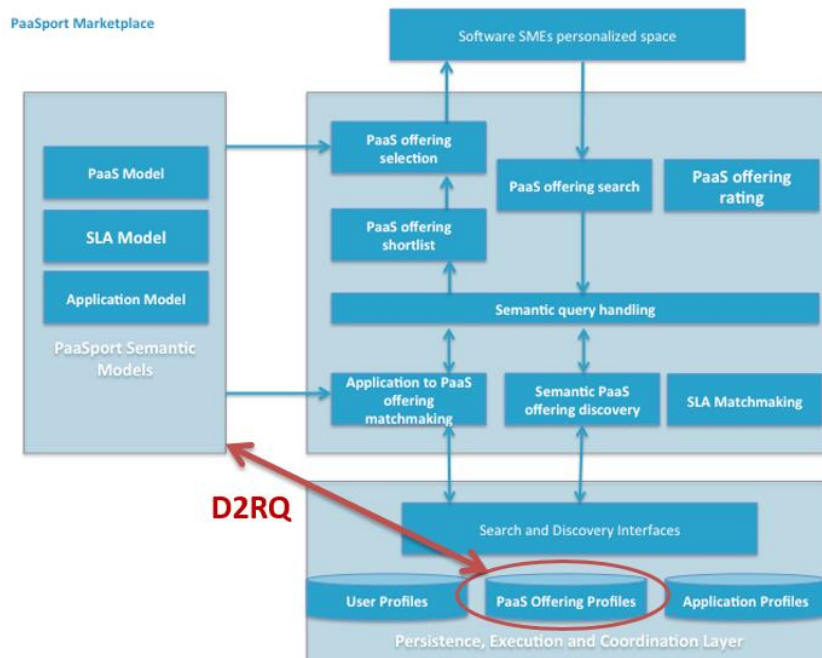
<sup>16</sup> Results of the evaluation are included in the Deliverable 6.3 "PaaSport Demonstrators documentation, Evaluation and Lessons Learnt", which is confidential, therefore only a portion of it will be presented here.

just any type of question will suffice. **Table 10** contains the results of the questionnaires regarding the questions related to the PaaSport semantic models. The answers to the questions were in a Likert scale from 1 to 5 (1 = most negative response, 5 = most positive response). Results show that most aspects of PaaSport related to the semantic models were scored on average positively (above 3), especially those related to the semantic annotations (shadowed rows in **Table 10**), which are directly related to the ontological concepts and properties, whereas the rest of the questions are related to the semantic search feature, which depends also on the implementation of the rest of the PaaSport platform layers, namely the user interface and the recommendation layers.

### 5.3 Application based evaluation

According to [77] one of the most handy methods for evaluating an ontology is when this is used in an ontology-based application. So, the purpose of this evaluation is to judge whether the ontology blends well with the rest of the system components and if it interoperates with them seamlessly. In the case of PaaSport the ontology strongly interacts with the PaaSport Semantic Model interacts mainly with the Recommendation and the Persistence layers of the PaaSport Broker (**Figure 20**). The interaction with the Recommendation layer has been fully presented, analyzed and evaluated in [5]. In this paper, we will present how the PaaSport semantic models interact with the Persistence layer.

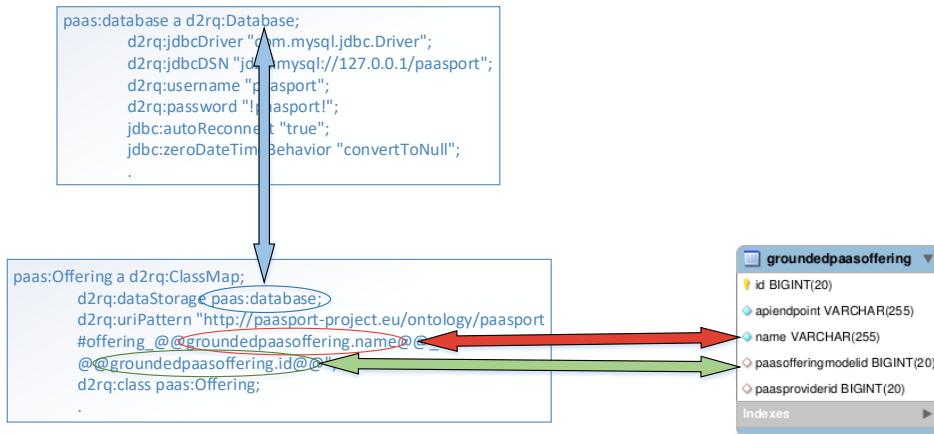
The Persistence (or Repository) Layer is used in order to (a) persist the various PaaSport data models that are mapped to the semantic model, (b) persist other entities that are needed for the proper function of PaaSport Marketplace, and (c) offer search and discovery interfaces that allow the usage of persisted information from other components. The main component of the persistence layer is a Relational database that is used to store the data that are necessary for the operation of the platform. The repository contains the three main types of data objects that PaaSport Marketplace needs to store: a) the PaaS Offering Profiles constituting the semantic profiles of the PaaS offerings advertised in the PaaSport Marketplace; b) the Deployed Application Profiles constituting the semantic profiles of the deployed business software applications; and c) the User Profiles constituting the semantic representation of the profiles that Software SMEs Engineers and PaaS Providers maintain on the PaaSport Marketplace.



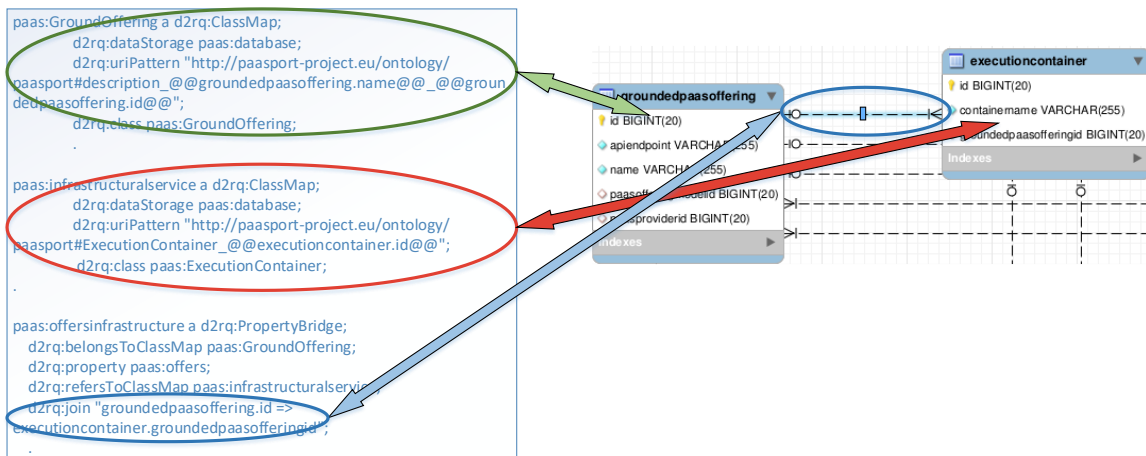
**Figure 20.** Relational to RDF mapping

In PaaSport we use the D2RQ Platform [17], and especially its D2RQ mapping language, a declarative language for mapping relational database schemas to RDF vocabularies and OWL ontologies, in order to export the offering profiles from the relational database of the persistence layer to an RDF format (**Figure 20**), so that they can be used by the matchmaking and ranking algorithm of the recommendation

layer [5]. The D2RQ language connects RDF triples to database tuples and attributes. **Figure 21** shows an example of a mapping rule for the grounded offerings. First, there is a rule for connecting to the database, so it defines the port of the database endpoint, username and password. After that, a mapping rule is defined, with the name of the rule-triplet, the defined data storage, the URI pattern of the triplets and the name of the class. Thus, for every tuple in the table *groundedpaasoffering* the mapping rule creates a new triplet. In **Figure 22**, a property-mapping example is presented. First, there is a rule that creates the property domain class (*GroundOffering* class). Then, there is a rule that creates the property range class (*ExecutionContainer* class). Finally, there is a rule that makes the property mapping, in our case, the property *paas:offers*. The connection is based on a join between the tables of the two classes above on the *id* attribute. Thus, every *GroundOffering* instance connects to a corresponding *ExecutionContainer* instance through the property *offers*, based on the *id* of the *groundpaasoffering* tuple.



**Figure 21.** D2RQ example; connecting to the database and mapping a table



**Figure 22.** D2RQ example; mapping a property.

At this point, it is worth mentioning that, alternatively, the platform offerings could have been stored directly into a native RDF database (i.e. a triplestore), so that all the above effort on converting relational data to RDF data could have been avoided. Notice, however, that the technology stack of the PaaSPort broker is based on the Spring Framework [69], Spring Data [68], and Hibernate ORM [37], which conjunctively offer fast development times [57]; therefore, it is inevitable to use a relational database system to store the data objects that are required in order for all PaaSPort layers to interoperate. Therefore, if we have chosen to duplicate data about platform offerings into an RDF database, we would have the additional complication of synchronizing data between the two database systems, which would be even worse than the complication of extracting data in an RDF format.

Concluding, the fact that the interaction of the PaaSPort semantic models with the Recommendation and Persistence layers was successful is another indication for the validity of the ontology.

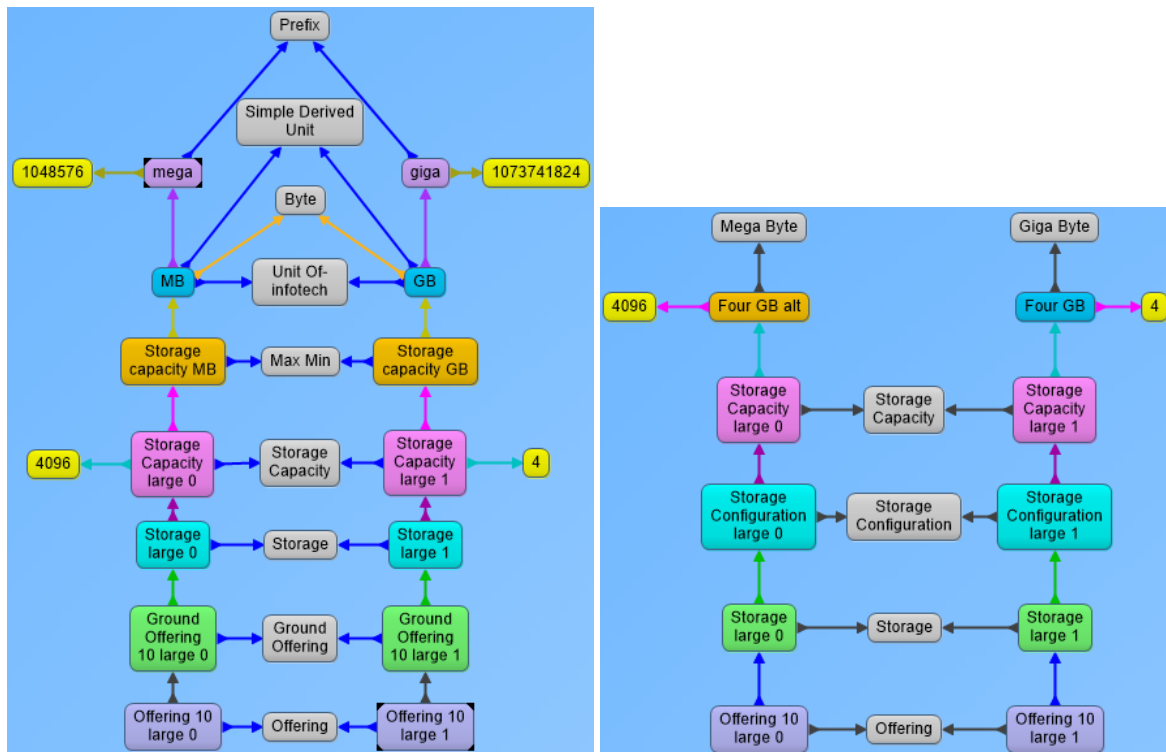
## 5.4 Ontology Scalability

To evaluate the scalability of the ontology regarding size and query performance and compare it with “competing” ontologies, such as Cloud4SOA [39], we have performed the following experiments:

- Scalability of performance for queries over platform characteristics that bear different measurement units vs. queries that are not concerned with units, using the PaaSport ontology. In this way, we will be able to evaluate the performance burden of having different measurement units.
- Scalability of performance for queries (with and without measurement units) over the PaaSport semantic model vs. similar queries over a Cloud4SOA-like semantic model. In this way, we will be able to evaluate the performance burden of having an extensible semantic model on top of DUL.

In order to achieve these, we have generated three types of PaaS offerings multiple times and we measured the size and the response time of corresponding SPARQL queries that return all the offerings that exceed the minimum applications requirements set for a single platform characteristic. In this case, the characteristic is the storage capacity offered by the PaaS in three different settings 1, 2 and 4 GBs. In order to check just the scalability, we have also restricted the description of the offerings knowledge bases to just a single platform characteristic (storage capacity).

**Figure 23** (a) shows two such offerings, using the PaaSport semantic model, used in the experiments, whereas **Figure 23** (b) shows the corresponding offerings using the Cloud4SOA-like semantic model. For all the experiments, we have created five different knowledge bases with 300 up to 3 million offerings. The ratio of the storage capacities among these offerings was 1/3 from each of the capacities. Furthermore, we have used two different settings for the experiment knowledge bases; in the first setting half of the offerings have their storage capacities expressed in GB, whereas the other half in MB, whereas in the second setting all offerings have their storage capacities expressed in GB, which makes querying easier. This makes in total 4 different types of knowledge bases (PaaSport model with GB and MB, PaaSport model with GB only, Cloud4SOA-like model with GB and MB, Cloud4SOA-like model with GB only), each in 5 different sizes (300, 3K, 30K, 300K, 3M offerings).



**Figure 23.** The offerings of the (a) PaaSport semantic model and (b) Cloud4SOA-like model.

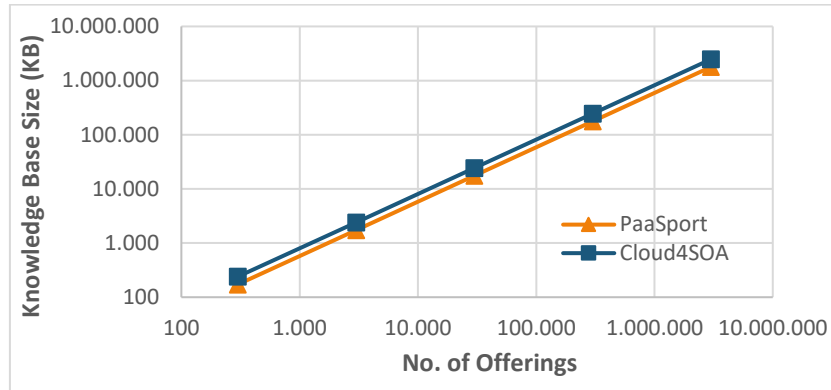
All knowledge bases (20 in total) were uploaded at corresponding repositories into Ontotext’s GraphDB Free<sup>17</sup> triplestore. Notice that in this paper we are not testing the ontology in the actual

<sup>17</sup> <http://graphdb.ontotext.com/>

PaaSport prototype, because we would like to evaluate just certain features of the ontology, regardless of the rest of the system implementation choices. The sizes of the knowledge bases are shown in **Table 11** and **Figure 24** (in KB) and they clearly scale linearly. Furthermore, there is not any notable difference between the PaaSport and the Cloud4SOA-like semantic models. Notice that only sizes of mixed GB-MB knowledge bases are reported; the corresponding knowledge bases with only GB have similar sizes.

**Table 11.** Size of offerings knowledge bases (in KB)

	300	3K	30K	300K	3M
PaaSport model	172	1,725	17,435	176,386	1,784,345
Cloud4SOA model	240	2,403	24,253	244,859	2,472,007



**Figure 24.** Scaling of offerings knowledge bases size.

The application request tested was for offerings with storage capacity at least 2GB, so the expected result set is comprised of 2/3 of the total number of offerings with 2GB and 4 GB storage capacity. The SPARQL queries for the four different types of knowledge bases are shown in **Listing 2**, **Listing 3**, **Listing 4**, and **Listing 5**.

**Listing 2.** SPARQL query for checking the storage capacity in the PaaSport semantic model (GB and MB).

```

1. SELECT ?offering ?Value WHERE {
2.     ?offering rdf:type paasport:Offering .
3.     ?offering DUL:satisfies ?gd .
4.     ?gd paasport:offers ?characteristic .
5.     ?characteristic rdf:type paasport:Storage .
6.     ?characteristic DUL:hasParameter ?par .
7.     ?par rdf:type paasport:StorageCapacity .
8.     ?par DUL:hasParameterDataValue ?Value .
9.     ?par DUL:parametrizes ?qualityVal .
10.    ?qualityVal uomvocab:measuredIn ?Units .
11.    ?Units rdf:type ucum:UnitOf-infotech .
12.    ucum:GB rdf:type uomvocab:SimpleDerivedUnit .
13.    ?Units rdf:type uomvocab:SimpleDerivedUnit .
14.    ?Units uomvocab:derivesFrom ucum:byte .
15.    ucum:GB uomvocab:modifierPrefix ?prefix1 .
16.    ?prefix1 uomvocab:factor ?Factor1 .
17.    ?Units uomvocab:modifierPrefix ?prefix2 .
18.    ?prefix2 uomvocab:factor ?Factor2 .
19.    FILTER ( ?Factor2*?Value >= ?Factor1*2 )
20. }

```

The SPARQL queries for the PaaSport model in **Listing 2** and **Listing 3** are simplified versions of the query templates presented in [5], adapted to the MinMax quality value of the storage capacity (see



section 4.3.5). Actually, they represent two of the measurement query cases; **Listing 2** takes into account the measurement units (because some of the storage capacities are in GB and some in MB, whereas the application request is expressed in GB) and **Listing 3** does not need to take into account the measurement unit, because the query designer knows in advance that all offerings use exactly the same measurement unit, in this case GB. More specifically, lines 2-8 in both listings iterate over all offerings and navigate to the Storage characteristic and the StorageCapacity parameter in order to retrieve its value. Then, in **Listing 3** line 9 simply ensures that the parameter is measured in GB and line 10 checks if an offering has an eligible parameter value. On the contrary, in **Listing 2** lines 9-10 retrieve the units that the parameter value is measured in and line 10 ensures that this unit is of the same type as the unit of the application requirement. Then, lines 11-14 ensure that both the units of the offering parameter and the application request are derived from the basic unit “byte”, while lines 15-18 retrieve the factors that the byte needs to be multiplied with in order to derive these units (e.g.  $2^{20}$  for GB,  $2^{30}$  for MB, etc.) Finally, line 19 transforms both values to bytes and compares them.

**Listing 3.** SPARQL query for checking the storage capacity in the PaaS semantic model (only GB).

```

1. SELECT ?offering ?Value WHERE {
2.     ?offering rdf:type paasport:Offering .
3.     ?offering DUL:satisfies ?gd .
4.     ?gd paasport:offers ?characteristic .
5.     ?characteristic rdf:type paasport:Storage .
6.     ?characteristic DUL:hasParameter ?par .
7.     ?par rdf:type paasport:StorageCapacity .
8.     ?par DUL:hasParameterDataValue ?Value .
9.     ?par DUL:parametrizes paasport:Storage_capacity_GB .
10.    FILTER ( ?Value >= 2 )
11. }

```

**Listing 4.** SPARQL query for checking the storage capacity in the Cloud4SOA-like semantic model (GB and MB).

```

1. SELECT ?offering ?Value WHERE {
2.     ?offering rdf:type c4s:Offering .
3.     ?offering c4s:offerStorage ?s .
4.     ?s c4s:hasStorageConfiguration ?sc .
5.     ?sc c4s:hasStorageCapacity ?par .
6.     ?par c4s:hasMaxStorageValue ?qualityValue .
7.     ?qualityValue c4s:hasValue ?Value .
8.     { ?qualityValue rdf:type c4s:GigaByte .
9.       FILTER( ?Value >= 2 )
10.    } UNION
11.    { ?qualityValue rdf:type c4s:MegaByte .
12.      FILTER ( ?Value >= 2048 )
13.    }
14. }

```

**Listing 5.** SPARQL query for checking the storage capacity in the Cloud4SOA-like semantic model (only GB).

```

1. SELECT ?offering ?Value WHERE {
2.     ?offering rdf:type c4s:Offering .
3.     ?offering c4s:offerStorage ?s .
4.     ?s c4s:hasStorageConfiguration ?sc .
5.     ?sc c4s:hasStorageCapacity ?par .
6.     ?par c4s:hasMaxStorageValue ?qualityValue .
7.     ?qualityValue c4s:hasValue ?Value .
8.     ?qualityValue rdf:type c4s:GigaByte .
9.     FILTER ( ?Value >= 2 )
10. }

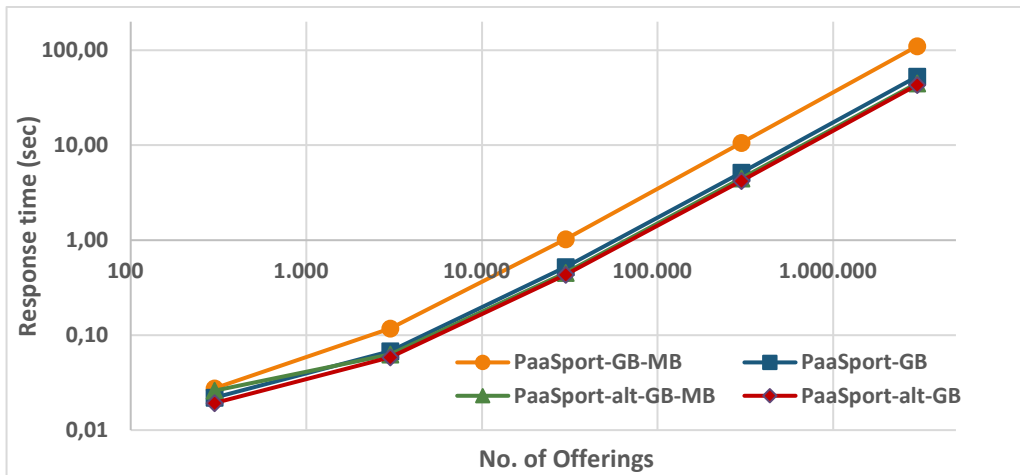
```

In the case of the Cloud4SOA-like semantic model, the corresponding SPARQL queries (**Listing 4**, **Listing 5**) navigate the graph of **Figure 23** (b). The first 7 lines are identical to both queries. Line 2 iterates over all offerings, whereas lines 3-6 navigate to the quality value of the maximum required storage capacity of the offering and line 7 retrieves the actual value. The query in **Listing 5**, first checks if the offered storage capacity value is in GB, and then it checks whether it is over the requested threshold. The query in **Listing 4** has a UNION in order to retrieve and check offerings whose storage capacity is expressed either in GB or MB.

**Table 12** includes the response times of all queries executed over all repositories. Each query was executed 30 times on a PC with i7 at 3.4 GHz CPU, 16 GB main memory and the average time is reported. **Figure 25** shows how the queries scale over the size of the triplestore (log-log scale). Results show that the query response time of the PaaSport semantic model with both GB and MB is approximately double compared to the other three types of models at most of the knowledge base sizes, except the “small” one with 300 offerings. This was expected since the PaaSport semantic model with alternative measurement units is more complex than the rest of the settings, therefore a more complex graph pattern is needed to retrieve the correct information. This is evident by just looking at the 4 different SPARQL queries. However, the burden of having alternative measurement units is not very big and the scaling of query performance of all model types is almost similar. In case only the GB measurement unit is involved, the comparison between the query performance of the PaaSport model and the Cloud4SOA-like model is even better (only ~22% worse).

**Table 12.** SPARQL query response times (in sec).

	300	3K	30K	300K	3M
PaaSport (GB-MB)	0.028	0.117	1.025	10.589	110.158
PaaSport (GB only)	0.022	0.068	0.522	5.162	52.790
Cloud4SOA (GB-MB)	0.026	0.063	0.454	4.471	44.855
Cloud4SOA (GB only)	0.019	0.058	0.433	4.200	43.103



**Figure 25.** Scaling of query response times.

From the above results, it is evident that the performance of the PaaSport model is inferior to that of a Cloud4SOA-like model, even if not significantly. Therefore, we should justify what the PaaSport model is better at. Notice that in all queries, the resources and properties indicated in bold are specific to the storage capacity request and need to be filled-in the query template for each different application request submitted by the user. These request-specific elements can be easily derived from the application request in the case of the PaaSport semantic model (**Listing 2**, **Listing 3**), whereas the rest of the query remains intact. This is because we have developed the PaaSport ontology as an extension of the DUL upper ontology, as we elaborated in section 4.2. However, this is not the case for the queries that use the Cloud4SOA-like model. The parts of the queries in **Listing 4**, and **Listing 5** that are highlighted need to be manually edited by the user each time a different characteristic is used as an application request.

This is because the Cloud4SOA ontology does not follow a regular structure as the PaaS ontology and the number, the names and the semantics of classes and properties of platform characteristics vary in an ad-hoc manner. This discussion also includes measurement units. For example, in **Listing 4** the transformation of the limit of 2GB to 20148MB needs to be done manually by the user, simply because there are no basic and derived units in Cloud4SOA and there is no way to automate the conversion between them. In case there are more alternative measurement units in the knowledge base, the query should be manually reformulated with more UNIONS, so there is a need from the user to know the contents of the knowledge base before submitting the query. In contrast, the query for the PaaS model in **Listing 2** works in any case of measurement units and for every measurable platform characteristic without any need for manual intervention. Concluding, PaaS trades flexibility and generality for performance. Since the number of PaaS offerings in a typical installation of the PaaS marketplace is not expected to exceed the order of few thousands, we believe that this trade-off pays off.

## 6 Conclusions and Future Work

The PaaS project tries to avoid the Cloud provider lock-in problem that many software SMEs are having, by (a) enabling platform provider SMEs to roll out semantically interoperable PaaS offerings, and, (b) facilitating software SMEs to seamlessly deploy (or migrate) business applications on the best-matching Cloud PaaS offering. To this end, PaaS combined Cloud PaaS technologies with lightweight semantics to specify and deliver a thin, non-intrusive Cloud broker, in the form of a Cloud PaaS Marketplace. In this paper, we have presented the semantical aspects of the PaaS Cloud broker / marketplace, focusing on an OWL ontology we have developed. The PaaS ontology represents the necessary PaaS characteristics and attributes for semantically representing: (a) capabilities of PaaS offerings, (b) requirements of applications to be deployed on one of the Cloud platform offerings, through a Cloud Broker, and (c) Service Level Agreements to be established between offering providers and application owners. The ontology has been designed to efficiently support a semantic matchmaking and ranking algorithm for recommending the best-matching Cloud PaaS offering to the application developer, which uses SPARQL queries for retrieving relevant data from the semantic repository.

The PaaS ontology has been defined as an extension of the DOLCE+DnS Ultralight (DUL) ontology [29]. This offers extensibility, since both PaaS characteristics and parameters are defined as classes, so extending the ontology with new characteristics requires just adding new classes as subclasses of existing ones, which is less complicated than adding properties. This extensibility advantage reflects also on the persistence layer of the PaaS marketplace that is based on a relational database system and it can be easily extended, as the semantic model evolves, without the need to change existing tables. Finally, this feature also proves to be advantageous in terms querying the knowledge base to retrieve PaaS offerings compatible with application requests. Specifically, general templates can be used to pose queries on any PaaS characteristic requested, including also arbitrary measurement units. This flexibility comes at a small performance price.

Comparing the PaaS ontology with the related Cloud4SOA ontology, the latter is broader concerning the management of the full lifecycle of cloud applications deployed at PaaS offerings, whereas PaaS is more focused on the aspect of matchmaking cloud application requests from PaaS offering characteristics. Furthermore, the user and enterprise layers are more detailed in Cloud4SOA, whereas the platform layer is more detailed in PaaS. The main advantages of PaaS over Cloud4SOA are: a) the fine handling of measurement units through the integration of the MUO ontology, b) the ability to check compliance of PaaS offering to application request parameters in a generic and systematic manner, without mentioning explicitly the PaaS characteristics and parameters involved, and c) the extensibility of the ontology concerning future PaaS characteristics and parameters. Both (b) and (c) are due to the use of the DUL upper ontology and the DnS design pattern.

Future development plans for the PaaS ontology include its extension with the representation of intricate PaaS pricing models and plans. Furthermore, a transformation methodology between these models is needed, so that these models can be comparable and useful in the decision-making about the Cloud platform to deploy an application, in addition to the recommendation algorithm [5]. This transformation can be based on inference rules, e.g. SWRL (Semantic Web Rule Language) [38] or SPIN (SPARQL Inferencing Notation) [41]. Finally, an interesting research direction would be to integrate the recommendation algorithm within the ontology in the form of SPIN / SPARQL [41] rules and constraints,

since the algorithm itself is mostly based on SPARQL query templates. In this way, the business logic of PaaS recommendation would be integrated with the ontology itself, making it transparent, modifiable, extensible and portable.

As far as the PaaS platform in general, a future challenge lies in the shift of the cloud market from virtual machines to containers, such as Docker<sup>18</sup>. Container engines are offered as a Service (CaaS) on top of cloud platforms, making application deployment, portability and migration easier for the DevOps engineer. Therefore, CaaS main purpose is to alleviate the main problem of PaaS adoption, namely the fact that it is too prescriptive for developers, a purpose similar to PaaS's. However, the PaaS broker and marketplace can still play a significant role in the CaaS era, helping DevOps engineers to select the best CaaS offer for the deployment of their application and aiding them to automate its deployment / migration, through platforms like Docker. Of course, before this is done the PaaS platform needs to evolve in order to embrace this new cloud paradigm.

## Acknowledgments

The authors would like to thank the anonymous reviewers for their insightful comments. This work is fully funded by the EU FP7-SME-2013-2-605193 PaaS project. The authors would like also to thank our project partners Giannis Ledakis, Andreas Papadopoulos, Demetris Trihinas, George Pallis, Gerald Hübsch, Fatemeh Ahmadi Zeleti, Sonya Abbas, Islam Hassan, Lukasz Porwol and Erdem Gulgener for their valuable comments on the PaaS ontology.

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<sup>18</sup> <https://www.docker.com/>

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