taxonomy is to identify and classify the fundamental IaaS components into ordered categories/layers, and use the taxonomy to compare and evaluate existing IaaS toolkits. We defined the following layers and components:

- Resource abstraction layer
  - Compute
  - Storage
  - Volume
  - Network
- Core service layer
  - Identity service
  - Scheduling
  - Image repository
  - Charging and billing
  - Logging
- Support layer
  - Message bus
  - Database
  - Transfer service
- Management layer
  - Management tools
    - CLI tools
    - APIs
    - Dashboard
    - Orchestrator
  - Resource management
  - Federation management
  - Elasticity management
  - User/group management
  - SLA definition
  - Monitoring
  - Reporting
  - Incident management
  - Power management
  - Lease management
- Security layer
  - Authentication
  - Authorization
  - Security groups
  - Single sign-on
  - Security monitoring
- Control layer
  - SLA enforcement
  - SLA monitoring
  - Metering
  - Policy control
  - Notification service
  - Orchestration
- Value-added services
  - Availability zones
  - High Availability
  - Hybrid support
  - Live migration
  - Portability support
  - Image contextualization
  - Virtual application support

The layers and components were identified based on 1) literature review of the most important commercial and open-source IaaS products in world of industry and academia [11], 2) investigation of current and future technological trends of IaaS paradigm [12], and 3) technical deployment and testing of individual IaaS system in several real-world projects.

The taxonomy consists of seven main layers: resource abstraction layer, core service layer, support layer that serves as a communication layer between core service layer and resource abstraction, security layer, management layer, control layer, and value-added services. The resource layer comprises basic virtualized resources of cloud infrastructures (compute, storage, volume and network). Core service layer encompasses components that present the core services of every IaaS system (i.e. identity service, scheduling, image repository, charging and billing, and logging). In addition, support layer acts as a middleware layer, providing means for other layers to communicate and interact. For instance, components within the core service layer that interact with the underlying resources are highly dependent on support layer in order to carry out their tasks. Those supporting components are message bus, database and transfer service. In addition, security layer plays an important role in IaaS cloud solutions, since security is one of the major barriers in adoption of cloud. Security layer includes authentication, authorization, security groups component, single sign-on and security monitoring. Furthermore, the crosscutting management layer consists of eleven components that are in charge of managing the entire cloud stack (i.e. management tools, federation management, elasticity management, resource management, user and group management, SLA definition, reporting, monitoring, incident management, power management and lease management). Moreover, control layer provides a cloud system with the basic control features, involving SLA enforcement, SLA monitoring, metering, policy control, notification service and orchestration component. Finally, the main purpose of value-added services is to provide components that are complimentary to a core service layer (i.e. multiple availability zones, High Availability (HA) support, hybrid cloud support, live migration, portability support, image contextualization and virtual application support).

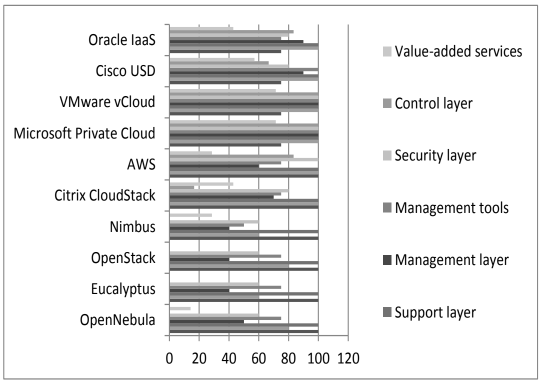

Figure 1. Mappings between the proposed taxonomy and chosen IaaS platforms.

We evaluated the classification by assessing five open-source and five commercial IaaS platforms, and mapped their capabilities to components and layers defined within our taxonomy. Fig. 1 illustrates mappings between the proposed taxonomy and chosen IaaS platforms. The values in the Fig. 2 indicate the average product coverage of IaaS taxonomy for the particular layer.

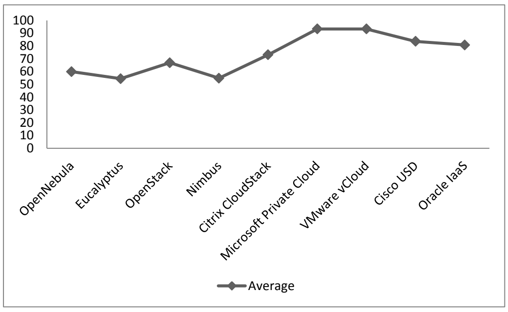

Figure 2. Average product coverage (%) of IaaS taxonomy.

TABLE I. COMPARING IAAS PLATFORMS USING A UNIFIED TAXONOMY – AN EXAMPLE OF MANAGEMENT LAYER.

Layers/Components	*OpenStack*	*AWS*	*Microsoft Private Cloud*	*VMware vCloud*
Management layer				
• Resource management	Internal	AWS Management Console	System Center Virtual Machine Manager (VMM)	vCenter Server
• Federation management	/	/	Within Hyper-V deployments, using Active Directory Federation Services (AD FS)	Within vCloud deployments, using vCloud Connector, vCenter Orchestrator.
• Elasticity management	/	Auto Scaling	System Center Orchestrator	vCenter Orchestrator
• User/group management	Internal	IAM, AWS MFA	VMM	vCloud Director
• SLA definition	Framework would have to be adjusted to work with existing SLA components	Internal	Internal	vCloud Service Definition
• Monitoring	Only external	CloudWatch	System Center Operations Manager	vCloud Infrastructure Management
• Reporting	/	AWS Management Console	Reporting Dashboard	vCenter Chargeback
• Incident management	/	/	System Center Operations Manager	vCloud Operations Management (Incident and Problem Management)
• Power management	/	/	System Center Configuration Manager	Distributed Power Management (DPM)
• Lease management	/	/	Service Manager Self-Service Portal	vCloud Director
Management tools				
• CLI tools	Euca2ools, VNC Console	Command-line access to EC2 and S3	Powershell	vSphere Command-Line
• APIs	OpenStack API, EC2 API, S3 API, Swift API, Glence API	APIs provided for most AWS services	Hyper-V WMI	vCloud API
• Dashboard	OpenStack Dashboard, Horizon	AWS Management Console	VMM SSP, Service Manager Self-Service Portal, App Controller	vCloud Director
• Orchestrator	/	/	System Center Orchestrator	vCenter Orchestrator

IV. EVALUATION AND RESULTS

The proposed taxonomy has been used for evaluating different IaaS architectures in several real-world projects, involving most widely accepted commercial and open-source IaaS solutions. In our example, evaluation was performed through comparison and analysis of four IaaS solutions: OpenStack, Amazon AWS, Microsoft Private Cloud and VMware vCloud. In order to compare the IaaS according to the taxonomy, each IaaS platform has been analyzed and tested, relying on comprehensive literature study and technical deployment (testing). The comparison showed the feature support and capabilities of each solution, and indicated how each capability fits into layers and components of our taxonomy. The value "/" in the comparison table (Table I shows an example of management layer alignment) presents the lack of particular feature support, while the value "Internal" indicates the built-in feature support with no particular naming. Other values present the concrete technologies that suffice components of our proposed taxonomy. Having a holistic evaluation taxonomy for a wide range of products creates an essential comparison baseline which allows IT departments to make educated decisions in adapting most suitable technology.

Besides built-in monitoring and autoscaling support, open-source toolkits are lacking some important features, such as virtual application support, orchestration support, incident management, power management, billing, logging, metering, SLA management, etc. For instance, the monitoring tools are in most cases available only as third-party solutions and have to be integrated with existing open-source frameworks. In particular, the integration can present major difficulties, if the IaaS framework is not designed to support such connectivity. To illustrate, Eucalyptus source package includes shell scripts, which modify Nagios and Ganglia configuration files to enable Eucalyptus-specific monitoring on predefined number of hosts. Moreover, the majority of public cloud offerings (e.g. Amazon EC2 using CloudWatch) provide an automatic scaling in response to load increases and decreases, relying on their built-it monitoring solutions. However, this is not the case with open-source IaaS systems, hence presenting an opportunity to implement extensions for automatic scaling in response to load in order to conserve resources and cost.

In case of delivering cloud services to end-users via pay-as-you-go business model, most mechanisms mentioned in previous paragraph (e.g. metering, billing and monitoring) have to be provided. In fact, this exact model is usually the main driver towards adopting Cloud Computing in organizations, since it is one of the reasons for significant cost reduction. On the contrary, commercial solutions support most of those features, but still do not entirely fulfill a promise of Cloud Computing paradigm. Hence, lacking portability support, image contextualization and provide hybrid cloud and federation management capabilities only within proprietary deployments. For example, VMware's solution provides hybrid cloud support leveraging vCloud Connector and is achievable only within vSphere supported clouds. Finally, while analyzing and comparing different IaaS architectures, some key downsides, and also opportunities for future development were identified. In order to truly deliver the Cloud Computing vision, deficient features of current architectures will have to be addressed in the future.

The proposed taxonomy was tested on several real-world projects, including KC OpComm (Project A), KC Class (Project B), SLA@SOI (Project C), Contrail (Project D), and one project for the largest Telco operator in Slovenia (Project E). Fig. 3 indicates the number of evaluated IaaS systems and number of chosen systems, while figure Fig. 4 illustrates the success rate of particular project. This metric was calculated as a ratio between the number of chosen IaaS systems and the sum of overall number of evaluated systems and evaluation period (calculated in months). In terms of decision making within IT organizations, project B has been considered as the most successful and project C as the least successful. At least one suitable infrastructure cloud solution has been chosen in every project, indicating a real-world usability and an efficient validation of the proposed architectural framework.

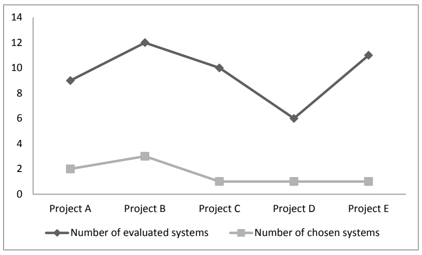

Figure 3. Number of evaluated/chosen IaaS systems.

The evaluation has shown 1) notable distinction of feature support and capabilities between commercial and open-source IaaS platforms, 2) significant deficiency of important architectural components in terms of fulfilling true promise of infrastructure clouds, and 3) real-world usability of the proposed architectural framework that facilitates the decision making in IT organizations for choosing the most suitable IaaS cloud solution.

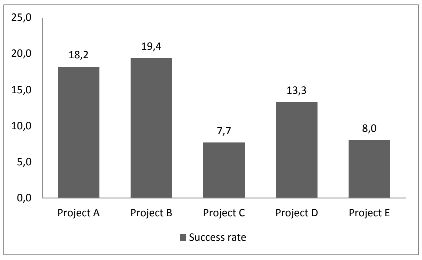

Figure 4. Success rate of particular project.

V. CONCLUSION

Many organizations do not take advantage of IaaS solutions because of uncertainty and a lack of information about their capabilities. From the comparison of IaaS systems, IT organizations can better understand the different IaaS platforms and more reasonably choose the most suitable one. Therefore, a mechanism for common understanding of IaaS technologies is required. In this paper, we developed a comprehensive taxonomy for describing IaaS architecture. The purpose of our taxonomy was to identify and classify the fundamental IaaS components into ordered categories/layers. We structured the taxonomy around seven layers: core service layer, support layer, value-added services, control layer, management layer, security layer and resource abstraction layer. We surveyed various IaaS systems and mapped them onto our taxonomy to evaluate the classification. Using the taxonomy and survey results we identified similarities and differences of IaaS architectural approaches, identified areas requiring further research, and showed real-world usability of the proposed taxonomy.

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