Abstract
Nowadays, cloud computing is one of the most used information technologies. It offers an infrastructure, a platform or a software as a service over the network to the huge number of remote users. Currently, this is a very promising and popular way in which they are offered. Cloud computing has a potential to change the using of information technologies.

There are two main open problems in cloud computing – interoperability and privacy. Our dissertation thesis is focused on interoperability. Nowadays it is difficult to migrate an application between clouds offered by different providers. The thesis deals with this problem in multicloud environment. Specifically, it is focused on an application performance optimization in a multicloud environment. A new method is suggested based on the state of the art. The method is divided into three parts: a multicloud architecture, a method of a horizontal scalability and a taxonomy for multicriteria optimization. The principles of the method have been applied in a design of a multicriteria optimization architecture, which we verified experimentally. The aim of the experiment is carried on a portal offered a platform according to the users’ requirements.

Categories and Subject Descriptors

Keywords
cloud computing, multicloud computing, architecture, multicriteria optimization

1. Introduction

Cloud computing is in the top 10 strategic technology trends for 2015 [9]. It is used by an academic field as well as by an industrial field. One of the main reasons for the expansion of cloud computing is the need for high-performance computing in almost every modern area. Users are requiring two main properties from clouds:

1. interoperability
2. privacy

Dissertation thesis is focused on interoperability. An intercloud migration of an application still represents a serious issue. Almost every cloud provider offers their cloud resources through specific API. Such an approach causes vendor lock in. The users have to adapt to provider’s API. Nowadays there is not a standard API or a reference cloud implementation.

The thesis is an extension of Minh Binh Nguyen’s research [13]. He created a generic development and deployment framework for cloud computing. The model solves interoperability on an operating system level. This thesis improves the model, in order to carry out an application performance optimization in a multicloud environment.

1.1 Motivation

Multicloud computing is advantageous for users as well as providers. The main advantages are: unified cloud-based architecture, avoiding of vendor lock-in, interoperability, scalability, improved accessibility, reduced latency and reduced operating cost.

There exist four fundamental cloud-based collaboration use cases [19]:

- hybrid cloud
- multicloud computing
- federated cloud
- Inter-cloud
Users of a hybrid cloud utilize a public cloud partly (e.g. resources of private cloud are insufficient). Alternatively, the users offer their unused resources to cloud providers. A hybrid cloud represents a resources’ extension of a private cloud.

Users of a multicloud computing work in a third party environment. The provider of the environment offers interoperability. That means the provider translates messages from different end-users to cloud providers and vice versa. However the management of resources is left to the end-users in many cases.

The concept of an inter-cloud was introduced by Cisco [2]. The paper describes the inter-cloud as a cloud made up of different clouds. This is a parallel to the Internet – the network of networks. Inter-cloud is characterized as a group of clouds which communicates through uniform standards. The standards provide cloud interoperability to users. This model has been inspired by Internet and telephone networks. It is typical for them that, in spite of infrastructure offered by different providers, all elements are interconnected.

Federated cloud is an aggregation of multiple cloud providers which offers its resources to improve services of individual cloud providers [11]. The providers made their idle resources available to each other. This policy improves scalability and flexibility across the federation. Thus, users work with resources that come from different providers. This property does not increase the load of the system. It is also irrelevant from the point of view of the system.

Federated cloud, Inter-cloud and multicloud computing are very new concepts. Computer scientists use them often interchangeably. We look at Inter-cloud as a global federated cloud. So the federated cloud is a first step towards Inter-cloud. Multicloud computing is an abstract concept that is an expression of the fundamentals of Inter-cloud and federated cloud.

2. State of the Art

There is a very good chance that the next evolution step of cloud computing will be distributed cloud computing – multicloud computing. Authors of paper [6] identified three evolutionary steps: monolithic, vertical supply chain and horizontal federation. Cloud services are offered by a single provider in the monolithic stage. Next step is to offer a pipelined cloud service. The whole service is offered by multiple providers. The providers create a vertical supply chain at the end of which is the service offered to a user. The last step is horizontal federation. Providers create a federation in which they share resources among themselves. This approach makes their services more reliable and improves scalability of their services. On the other hand, it is the interaction of the providers, which represents the greatest challenge.

Currently there dominate monolithic cloud services (Amazon, Google, Microsoft . . . ). Each provider has their own API which makes service administration and maintenance complicated. Consequently, a user is restricted by one provider in many cases. It is very difficult to collaborate with many providers and cloud services combining is not supported. The heterogeneity causes vendor lock-in [17, 14]. That means, a user becomes dependent on the provider. Users are unable to replace their provider without effort. This situation suits cloud providers who do not engage in it at all [15].

There are two main ways to achieve multicloud computing [19]:

- collaborative service (middleware)
- standardization (e.g. interfaces)

A collaborative service is an intermediary between a user interface and cloud. Its task is to ensure communication between cloud interfaces (e.g. by messages translating). This approach allows customers to use clouds from different providers. It ensures cloud interoperability. Standardization offers another way to ensure interoperability (e.g. this approach was successful at network communication – it creates TCP/IP protocols). Currently, it is very difficult to obtain standardization, so we decided to create a collaborative service.

2.1 Standards Supporting a Multicloud Computing

The following table of standards has been based on the survey [19]. It implies two important facts. The facts influenced us in our research.

The first fact is that a design of a standard for multicloud computing deals with three main factors: interoperability, security and legality (of the service in a particular country). Other obstacles are following. Cloud providers do not want to agree on a uniform standard. They rather prefer vendor lock-in [14].

The second fact is that there have been produced many standards, but neither of them has become a globally recognized for multicloud computing [14, 19] (see table 1). It is a consequence that the providers are not able to agree on a single standard and this situation suits them also. We decided to focus on collaborative services only, based on these facts.

2.2 Collaborative Services

Various collaborative services are discussed in this subsection. This is the best way to achieve multicloud computing, taking into account the current situation. The services can be performed either on a user’s side or can be offered as a third party service. Following analyse of collaborative services is based on the survey [19].

Reservoir [17] is an architecture for a cloud federation. The authors distinguish between two operations in the model. That also means the model has two types Reservoir sites – infrastructure providers’ sites and service providers’ sites. Service providers offer their customers the applications that exploits an infrastructure provided by infrastructure providers. Service providers do not own a computing resources, network or storage. Those are owned by infrastructure providers who offer them to service providers in the form of isolated virtual environments – virtual execution environment (VEE).

Architecture Reservoir has three main components: service manager, virtual execution environment manager and virtual execution environment host.
### Table 1: The table compares current standards according to the focused problem – Provisioning (Pr), Portability (Po), Service Level Agreement (SLA), Security (S), Monitoring (M), Economy (E), Network (N), Autonomas (A). (Adapted from [19].)

<table>
<thead>
<tr>
<th>Standard</th>
<th>Pr</th>
<th>Po</th>
<th>SLA</th>
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<td>GICTF (The European Telecommunications Standards Institute)</td>
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<td>IEEE P2302 (IEEE P2302 Working Group)</td>
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<td>SNIA CSI (Storage Networking Industry Association (SNIA) Cloud Storage Initiative)</td>
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<td>ISO JTC 1/SC 38 (ISO JTC 1/SC 38)</td>
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<td>ITU-T FG (ITU-T Focus Group on Cloud Computing)</td>
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<td>SIENA (Standards and Interoperability for eInfrastructure implementation initiative)</td>
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</table>

### Table 2: The table compares the multicloud collaborative services – focus of the project (F), type of the project (T), interoperability achieving (I), provider side installation (P), client side installation (C).

<table>
<thead>
<tr>
<th>Project</th>
<th>F</th>
<th>T</th>
<th>I</th>
<th>P</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir</td>
<td>interoperability</td>
<td>architecture</td>
<td>standardization</td>
<td>✓</td>
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<tr>
<td>Contrail</td>
<td>interoperability</td>
<td>architecture</td>
<td>agent approach</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>OPTIMIS</td>
<td>efficient use of resources</td>
<td>software tools</td>
<td>agent approach</td>
<td>✓</td>
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</tr>
</tbody>
</table>

The service manager is on the top layer. It interacts with service providers – it receives their service manifests (e.g. deploy virtual environments, SLA monitoring . . . ). Middle layer is virtual execution environment manager. Its role is to manage a virtual environment, to interact with virtual execution environment manager of other pages (this property creates a federative cloud) and to place virtual environments into virtual execution environment hosts. Bottom layer is virtual execution environment host. It is responsible for supporting various types of virtualization, virtual environment monitoring and provide migration of a virtual environment within a federated cloud.

**Contrail** [5] enables the utilization of cloud resources offered by different cloud providers (horizontal integration) and also it gives an opportunity to work with IaaS and PaaS (vertical integration). Contrail is based on agents who act as intermediaries between cloud users and cloud providers. Contrail consists of three layers: interface, core and adapters. The interface layer has two forms – command line and web interface. Its role is to collect requirements from users and provide services of a federated cloud as a REST service. Core layer contains modules for security, application management and SLA management. The federation runtime manager looks after the application management which exploits services of the image manager and provider watcher. Adapters layer is a bottom layer. Adapters are subdivided by type of resources provided into external and internal modules. Internal modules make available virtual infrastructure network, global autonomous file system and virtual execution platform. External modules translate messages from federated cloud to cloud providers.

**OPTIMIS** The main components of OPTIMIS are as follows. Services are created by the service builder. It has integrated development environment that allows a development (via programming model) and a configuration (via configuration manager). SaaS cloud is gotten at the end (a service is offered over the Internet and it is executed in multicloud environment). Basic toolkit supply a functionality for service management (e.g. monitoring, security . . . ) to other components. Once an assembling of a service is finished, deploying of the service is started. Deploying is carried out with deployment engine. It looks for the best infrastructure provider for the service. If the search is successful, deployment engine sends a request to admission controller. The admission controller decides if the service exploits the resources of the infrastructure. Subsequently, cloud optimizer allocates the resources for the new service. Successful deployment of the service is reported to service optimizer. Afterwards, the service is observed by service optimizer which is able to make its subsequent migration to the other infrastructure, if it is necessary and the service level agreement is not broken.

**Comparison of the collaborative services.** Three significant research projects related to our research have been identified during the analysis of the state of the art: Reservoir, Contrail, and OPTIMIS. The comparison is summarized in the table 2. Several important observations have been made on the basis of the table. OPTIMIS focuses on an optimization and is the extension of an (multi)cloud
architecture. It is the set of software tools, while the other
two projects focus on interoperability and multicloud ar-
chitectures. Reservoir achieves interoperability through
standardization. This is the reason for the installation on
a provider side as well as on a client side. Contrail and
OPTIMIS do not rely on standardization and therefore
are installed only on client side. They achieve interoper-
ability through agent approach.

3. Main Objectivities of Dissertation Thesis
Building on these ideas, our architecture is created. From
state of the art, we made several observations:

1. Nowadays, there are many cloud providers offering a
cloud service through a proprietary API (e.g. Amaz-
on, Microsoft . . . ). This situation creates vendor
lock-in [17, 14].

2. Cloud’s customers mostly focus on two types of
clouds – SaaS and IaaS [17]. This is due to that a
platform (in the current form) is suitable for small
group of users. The situation is a result of two fac-
tors. If the user is interested in a particular product,
they choose a SaaS. On the other hand, if the user
wants to be more variable (or they are interested in
a virtualized environment), they are forced to use
IaaS currently. PaaS appears to be only suitable at
first glance (see section 2). That is the reason why
the dissertation thesis is focused on IaaS at multi-
cloud computing environment.

3. There are several ways to achieve multicloud com-
puting [15]. The most common ways are a standard-
ization of interfaces and collaborative services. The
state of the art shows that the standardization
is very difficult to enforce. This is due to the
fact that today’s cloud providers refusing to accept
a common interface [19]. That is the reason why
the article presents a collaborative service.

4. Collaborative services offering infrastructure is a
young field of cloud computing. There exist only
several projects focusing on the services. The arti-
cle has presented three FP7 – Reservoir [17], Con-
trail [5] and OPTIMIS [8]. The main difference
between these projects is the way an interoperabil-
ity is achieved. Reservoir has to be carried out on
multicloud provider’s side. This approach has the
same problem as standardization – the providers
have to agree on it. Contrail and OPTIMIS take
reverse approach – the collaborative service is ex-
ecuted on user’s side (alternatively it can be pro-
vided as a service). This approach is independent
of the providers because the services are located be-
tween the providers and the users. Contrail applies
an agent approach to achieve multicloud services.
However the approach is redundant (it is too high
load on a network). In this case, the agents are used
for a discovery and selection of resources. OPTIMIS
is not an architecture, it is a software kit allowing
some kind of an optimization.

The main ideas that influenced the design of the architec-
ture are as follows:

- allow scalability
- allow interoperability
- avoid vendor lock-in
- provide infrastructure primary (in order to be ex-
tensible, the design has to flexible sufficiently)
- create collaborative service
- be independent of providers
- allow flexible provider administration (new provider
changes the architecture minimally)

4. Multicloud Computing Architecture
Let us start with a characterization of a multicloud prob-
lematic (see problem 1). This approach enables us to
make a method for this problem.

PROBLEM 1. Multicloud computing
Input: virtual resources VR from different providers
Problem: to merge virtual resources VR in order to be
accessible by an uniform way
Output: multicloud virtual resources MVR

The description of proposed architecture employs the
model of abstract resources created by Minh Binh Nguyen
(see paper [13]). The formalism of multicloud computing
was derived from problem 1. A whole multicloud with
k virtual machines is labelled as Ck. Detailed definition
looks as follows [9].

DEFINITION 1. Multicloud computing
Multicloud architecture is represented by a (k+1)–tuple
Ck = (VM1, . . . , VMk, M), where VMi is an abstract vir-
tual machine and M is a cloud middleware of a multicloud
environment.

Software SWi = (BaseSW, App1, . . . , Appn) of an ab-
stract virtual machine VMi from Ck has to satisfy the
following condition:

∀1 ≤ i ≤ n ∃1 ≤ j1, . . . , jn ≤ n :
check(App1, . . . , Appj1, . . . , Appjn).

It is crystal clear that a tool for an application compatibil-
ity is needed. A predicate approach is supposed in this pa-
er. The paper present a predicate check(x, y1, . . . , ym).
The predicate ensures that applications from a virtual
machine are compatible.

DEFINITION 2. Abstract resources checking
check(x, y1, . . . , ym) is a predicate (check : {x, y1, . . . , ym} → {True, False}) which on input gets an abstract appli-
cation x and abstract applications y1, . . . , ym running on
the same virtual machine as x.

check(x, y1, . . . , ym) = \begin{cases} True & \text{if } \cup_{i=1}^{m} prov(yi) \\ False & \text{otherwise} \end{cases}

The predicate verifies if there is a conflict among appli-
cations running on the same virtual machine. The basic
view is that if an application requires a property then
another application running on the same virtual machine
provides the property.

DEFINITION 3. Abstract application interface
prov(x) = {v1, . . . , vn}, where vi is a property provided by
an application x.
req(x) = {v1, . . . , vn}, where vi is a property required by
an application x.
5. Methodology of a Horizontal Scalability

Let us start with a characterization of a multicriteria optimization as before (see problem 1).

**Problem 2. Multicriteria optimization**

**Input:** internal virtual resources $VR^1$, set of optimization criteria $OC$.

**Problem:** to reallocate internal virtual resources $VR$ based on the requirements $OC$ with respect to running applications in the cloud.

**Output:** internal virtual resources $VR'$

The methodology works in the multicloud architecture. The main advantage of the architecture is that it operates with applications as independent components. This approach allows to run the methodology on a virtual machine’s level. It supports a creation of a virtual machine, a deletion of a virtual machine or a migration of an application among virtual machines as necessary. So a formal definition looks like follows [12].

**Definition 4. Intercloud multicriteria optimization**

Multicloud $C_k = (VM_1, \ldots, VM_k, M)$ is balanced if and only if:

$$\forall 1 \leq i \leq k : balanced(VM_i).$$

A concept of balanced multicloud expresses that a multicloud is balanced if and only if its every virtual machine is balanced.

**Definition 5. Virtual machine optimization**

$balanced(vm)$ is predicate (balanced : $\{vm\} \rightarrow \{True, False\}$), which gets a virtual machine $vm$ on input. Let us have a set of predicates $T$, which describes nonoptimality. The predicate is defined as follows:

$$balanced(vm) = \begin{cases} True & \forall p \in T : p(vm) = False \\ False & \text{otherwise} \end{cases}$$

System nonoptimality characterizes a set of rules (formally predicates), which we marked by letter $T$ (there are rules such as: the usage of a virtual machine processor is less than 30%, the usage of a virtual machine processor is more than 80% . . .).

6. Taxonomy for a Multicriteria Optimization in a Multicloud Environment

A taxonomy (see figure 1) describes a functional abstraction of a multicriteria optimization in a multicloud environment. The taxonomy is also composed from properties of entities. The basic entity is a multicloud. The multicloud offers an optimization (as defined in the definition 1). The optimization relates to a monitoring of criteria. The multicloud has to detect nonoptimal virtual
Let us explain the application of the multicriteria optimization method in the architecture design on an example. Let us have a multicloud that is composed of two clouds. Eucalyptus is installed on the first cloud and OpenStack is installed on the second cloud. The multicloud architecture has to have drivers for both environments. The driver functionality is represented by element $M$ in the definition of multicloud computing (see definition 1). Let us have four virtual machines – $C_A = \{VM_1, VM_2, VM_3, VM_4\}$, $M_{Eucalyptus, OpenStack}$. The virtual machines have installed Unix-based operating system (e.g. Linux Ubuntu – $\forall i \in \{1, 2, 3, 4\}$ SW$_i$ : BaseSW = Ubuntu14.04). Compliance of software interfaces is simplified by the installation from repositories. In case the repositories are unavailable, this functionality has to be ensured within the architecture (as stipulated in the formal model of the multicloud architecture).

The algorithm 1 also gets the set of predicates $T$. The set expresses the imbalance of the system. The predicates are divided into two parts in the algorithm. The first part consists of the conditions of imbalance (it is represented as tuple $C$). The second part is contains events, that allow a transition from an imbalanced state $c$ to a balanced state $r_i$ (it is represented as tuple $R$).

The multicriteria optimization is divided into several sub-optimizations which are represented by the set $T$. Each predicate corresponds to one partial optimization. Thus the state of the system is not defined by one criterion, but by $n$ criteria where $n = |T|^2$.

The aim of our optimization approach is to search events from $R$, which enable a transition to a more balanced system. The event can be imagined as a virtual machine configuration change (e.g. performance of processor, size of RAM and so on). Virtual machines are monitored regularly, and if imbalanced is occurred, the relevant event is performed.

Let us have a user who does not want to waste of processor performance and RAM – $C = (\text{usage of CPU } < 30\%$, usage of RAM $< 30\%)$ and $R = (\text{reduction of processor frequency, reduce of RAM})$. Monitoring tools check the actual status of CPU and RAM of every virtual machine in the multicloud system. If there is waste of resources, then relevant event is carried out.

This approach is inspired by the hill climbing search algorithm [18]. The algorithm is one of the basic approaches which searches the space of states (locally). The actual state is replaced by better neighbouring state in each iteration of the algorithm. It belongs to the greedy algorithms [7].

The main contribution of our method is the automatic configuration of virtual machines due to actual usage. If we would like to compare a nonoptimized system with an optimized system, the main benefit is in an effective allocation of multicloud resources. A provider gets a more balanced load of clouds. A user’s virtual machines work only with the resources of the multicloud system which they are using actively. This is one of the main character-

2The tuples $C$ and $R$ has the number of elements equal to the cardinality of the set $T$. It is a direct consequence of the definitions of the tuples.
istics of cloud computing - pay as you go. This property is not ensured within infrastructures offered as a (cloud) service.

8. Implementation

The implementation is based on the results of previous sections. It is composed of three components (see figure 2): multicloud interface, multicloud manager and cloud driver. Whole implementation is made in Python.

Multicloud interface obtains requests from users and it offers multicloud services in form of REST services. Multicloud manager carries out a integrity of cloud resources provided by different providers and it processes requests from users. The last part of the implementation is cloud driver. Cloud driver transforms a requests which were sent between a cloud manager and a cloud provider.

For a multicriteria optimization, multicloud manager has been extended by monitoring tools and optimization algorithm. In order to know the actual state of a virtual machine load, monitoring tools have been implemented into the multicloud manager. Monitoring is focused on an infrastructure. Virtual machines are monitored (e.g. processor, RAM, storage and so on) and this information is mediated to other subsystems. Nowadays, there are many monitoring tools for big distributed systems. However, the approaches are not usable straightforwardly in a multicloud environment. The main complication is a heterogeneous aspect of the environment. Cloud providers offer cloud services through a different API which makes monitoring difficult. The implementation is able to monitor cloud resources independent of cloud providers.

Monitoring information is important for an optimization algorithm (see algorithm 1). The algorithm controls whether all virtual machines satisfied every optimization condition. The algorithm is testing a balance of a virtual machine. If a criterion is not satisfied then the operations (defined by a user) addressing the situation are carried out. Multicloud interface is expanded with the possibility to enter an optimization criterion.

9. Experiment

Presented approach had been tested in an environment of tailored platforms – platforms created to users’ needs. The current situation implies that a future (cloud) services will be more plastic. This means that the services will be adapted to users not vice versa. However it cannot be achieved immediately. The technology has to grow up. The starting point could be to think about multicloud environments – platforms created according to users’ requirements. Nowadays platforms are preconstructed. Users need just such a platform that offers a provider or have to move to another type of cloud (it is often a cloud offering an infrastructure). This is problematic in many cases, especially for noninformatics users. Another important problems are caused by an integration of a software executing on the platform and lack of knowledge about an operating system. The characterization of tailored platforms is described by following problem (see problem 3).

**Problem 3. Tailored platform**

**Input:** internal virtual resources \( V_R \), a set of requests on a platform \( P_R \).

**Problem:** to reallocate internal virtual resources \( V_R \) into the tailored platform \( TP \) which satisfies the demands \( P_R \).

**Output:** tailored platform \( TP \).

\(^3\)For example, it could be virtual machines of IaaS
A portal (see figure 3) supporting tailored platforms is designed according to the problem 3. The portal consists of three parts: authentication, tailored platform provider and virtual machine manager [4]. The portal consists of multicloud resources. As has been mentioned, authentication is not taken to account. It is left to cloud providers.

Platforms have been represented as images. The user chooses an image and virtual machine configuration. The portal creates a platform based on these demands. Such simple approach allows us to give users some form of freedom in the platform context. The images (of platforms) could be prepared by portal provider or other users.

The runtime platform model (see figure 4) describes deployment the elements of the portal. The experiment was carried out on FedCloud’s clusters (on infrastructure offered by the Institute of Informatics of Slovak academy of sciences concretely). A cluster has 176 cores with 3 GB RAM and its storage is 50 TB. The biggest offered virtual machine has 8 cores with 16 GB RAM and its storage is 160 GB. Application server of the portal is Django since that portal is implemented at Python.

This work does not focus on security as has been mentioned before. Therefore user connects directly to the portal in a network model (see figure 5). Security issues are left on cloud providers.

9.1 Prototype

The experimental environment for the portal have been made. The achieved results have been verified through the prototype. That means, the architecture of the portal was multicloud with multicriteria optimization. The form of the prototype was dynamic web application. The application has two basic environment – the virtual machine manager and the manager of the optimization conditions.

Several properties are provided by the virtual machine manager. The active virtual machines are shown to the user. A virtual machine can be backed up or deleted. The virtual machine manager is responsible for a creation of a new virtual machine and a restoration of a virtual machine (from a snapshot). The user of the portal is not tied with one provider. The provider can be changed with a minimal effort (a provider name is one of the parameters of a creation or a restoration of a virtual machine). The remaining operations of the virtual machine manager are the commands for a virtual machine. The user is able to download or upload a data of a virtual machine and make a connection with a command line of the virtual machine. It is very important to note that the applications could not be very tied with the operating system. Portable applications are very suitable. The reason is that the application has to be able a intercloud migration. The manager of the optimization conditions provides basic functionality for the conditions – overview, creation and deletion of the conditions.

The main contribution of our approach is to make the sharing and allocating of multicloud resources as much effective as possible. An application should work with resources that are needed at the moment. It was achieved through the monitoring of a virtual machine load at regular intervals. Through the monitoring, unbalanced virtual machines had been detected, and they were transformed into balanced.

The balanced multicloud is also much more loaded as an unbalanced multicloud. This is due to the fact, an user makes an estimation of the resources amount needed by an application. However, the resources amount is too much larger. This phenomenon causes that the resources are artificially allocated, even if they could be used by other applications.

9.2 Description of the Experiment

The experiment simulated the load of the multicloud system and we observed as our approach increased effectiveness of the multicloud resources. Consequently, the optimized cloud was compared with unoptimized cloud.

The balanced multicloud is also much more loaded as an unbalanced multicloud. This is due to the fact, an user makes an estimation of the resources amount needed by an application. However, the resources amount is too much larger. This phenomenon causes that the resources are artificially allocated, even if they could be used by other applications.

The parameters of the experiment. The experiment was carried out on the infrastructure of the Institute of Informatics of the Slovak Academy of Sciences. We worked with three virtual machines at OpenStack environment. A user’s behaviour has been simulated in the environment. Optimization focused on RAM and CPU. The optimization rules were as follows: if CPU usage is greater than 80% increase the processor frequency; if CPU usage is less than 20% decrease the processor frequency; if RAM usage is greater than 80% increase size of RAM; if RAM usage is less than 20% decrease size of RAM. The monitoring of the virtual machines was carried out every 15 minutes.

The load simulation was performed by programs written in the programming language Python. The cause of load

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The OpenStack does not allow to change the processor frequency, but merely the number of processor cores. Therefore, the CPU usage has been represented as the sum of the load of all CPU cores and so the CPU frequency changing operation has been replaced by changing of the CPU core number.
is irrelevant from the point of view of the system behaviour. CPU load was simulated by the infinite loop, multicore load was carried out by parallel execution of the infinite loop and RAM load was performed by saving a large array into RAM.

The environment of OpenStack was not customized. It causes an issue with preconfigured virtual machines (see table 3), namely when we wanted to change one of the parameters of the virtual machine. This is not possible in OpenStack (other cloud environments behave similarly). If users want to change a parameter, they need to choose a different virtual machine configuration – so all parameters are changed. However, this may not be demanded. This unwanted effect can be solved by defining more preconfigured virtual machines.

**Design of the experiment.** The initial configuration of all virtual machines was medium with Ubuntu 14.04. Two virtual machines had CPU load at 15.3%. Another virtual machine had CPU load at 97.6%. All virtual machine had RAM load on 6.4%. This is a common situation. A user has to estimate the amount of resources that is needed in average. A low amount of resources slows down the virtual machine. A high amount of resources is uneconomical from user’s point of view. The result of the phenomenon is a time interval when the virtual machine has an inadequate amount of the resources.

Our optimization method adjusted the amount of allocated resources with regard to the actual need. Two virtual machines were running Ubuntu 14.04 only so they had been transformed into configuration small (configuration tiny does not satisfy the minimal hardware requirements of Ubuntu 14.04). The last virtual machine had been transformed into configuration large. Subsequently, the loads of virtual machines were changed and we observed the reaction of our approach on the actual load. The experiment is summarized in the table 4.

### Table 3: The table shows preconfigured virtual machines in OpenStack.

<table>
<thead>
<tr>
<th>CPU cores</th>
<th>Hard disk</th>
<th>RAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>tiny</td>
<td>1</td>
<td>1 GB</td>
</tr>
<tr>
<td>small</td>
<td>1</td>
<td>20 GB</td>
</tr>
<tr>
<td>medium</td>
<td>2</td>
<td>40 GB</td>
</tr>
<tr>
<td>large</td>
<td>4</td>
<td>80 GB</td>
</tr>
<tr>
<td>xlarge</td>
<td>8</td>
<td>160 GB</td>
</tr>
</tbody>
</table>

### Table 4: The table shows the configurations of the virtual machines during the experiment.

<table>
<thead>
<tr>
<th></th>
<th>15 min.</th>
<th>30 min.</th>
<th>45 min.</th>
<th>60 min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>VM 1</td>
<td>small</td>
<td>medium</td>
<td>small</td>
<td>small</td>
</tr>
<tr>
<td>VM 2</td>
<td>small</td>
<td>medium</td>
<td>large</td>
<td>xlarge</td>
</tr>
<tr>
<td>VM 3</td>
<td>large</td>
<td>medium</td>
<td>small</td>
<td>medium</td>
</tr>
</tbody>
</table>
9.4 Conclusions of the Experiment

Several conclusions have been made based on the experiment:

- **Vendor lock in can be dealt with interoperability** – the thesis shows that interoperability deals with vendor lock in adequately. A user is able without stronger efforts to change a provider of (multi)cloud services.

- **Support of multicloud environments and multicriteria optimization is insufficient** – it turns out that cloud computing will pass through similar developments as computer networks. The result of the evolution will be multcloud computing. However, it is not very widespread for obvious reasons. Thus the resource optimization is not sufficiently investigated. However, if multcloud computing is going to be the next step of cloud computing, it has to respect cloud computing – users pay as they go. This is maintained only if the resources are not wasted.

- **Collaborative service is more accepted than standard** – a form of (multi)cloud computing is a very important question. Nowadays, there are two forms: collaborative service and standard. Our research confirmed that there are certain advantages in the development of a collaborative service. The main reason is the model is independent from providers.

- **Application have to be portable** – if the migration is performed at the application level, then the application has to be as much independent of operating system as possible. The applications have to behave on the abstract level like containers with clearly defined interfaces.

- **Services have to be adaptable** – our experiment shows that flexible services represent a one way to improve the current status of PaaS. The users have not to adapt to services, but the services have to be able to adapt to the user.

10. Approach Contribution

Considering the current situation, there does not exist a method providing a multicritetrial in multicloud environment, we decided to compare our approach with current cloud providers and scientific multicloud projects (see table 5). There does not exist commercial multicloud environment. One of the biggest problems of cloud computing (in common form) is vendor lock-in. We propose to deal with the problem through interoperability, as other research groups.

Efficiency of virtual resources utilization is another problem which is equally important as previous problem. This aspect is important particularly for a cloud offering an infrastructure as a service (IaaS). Other cloud models have some mechanisms solving the problem by definition. Only IaaS users have to deal with it.

Amazon offers one of the most used IaaS’ cloud. It offers extensive monitoring tools as a CloudWatch. This tool allows some type of an optimization. A user is able to set up some alerts (they are similar with our optimization criteria) checking a load of cloud resources. However they are not resolved automatically. It is left to the user. Another significant cloud provider is Microsoft and its cloud Azure. However Microsoft is relying on that its products are used by every big corporation and so Microsoft decided to offer its products in virtual form over the Internet. Microsoft relieved its users of administration, however on the other hand it locked its users to a greater extent than Amazon. Similar way also chooses Google App Engine, Ruby on Rails and Salesforce.

The situation is quite similar in the cloud open-source projects. Other important characteristics of the projects are that they are “cloud operating systems” only. That means they do not own resources. This may be a problem for many users. Eucalyptus and OpenStack contain, as
well as Amazon, monitoring tools. Nevertheless, virtual machines utilization is not optimized in any way.

The situation is more interesting among research projects. Reservoir is an architecture for cloud federation. However development has shown that the architectural design does not take root. The reason is the same as with cloud standards. In order to care out of the architecture, it has to be installed on provider side also. Nowadays, the leading cloud providers do not want to merge with other providers. Therefore, an architecture has to be independent of providers. Reservoir, as well as Contrail, does not support optimization. OPTIMIS is the only project that supports both multicloud computing and optimization. However OPTIMIS focuses on SLA, while presented approach focuses on the user’s requirements.

The architecture is based on two aspects. First aspect, that lead us to create a new architecture is that the projects, mentioned above, do not offer a sufficient freedom to new providers of (multi)cloud services. We suggested also the new multicloud taxonomy for multicriteria optimization. The taxonomy clearly specifies a cloud functionality. Thus, if new providers want to be a part of a federation, then they just create a driver characterizing a dictionary of the taxonomy. The second aspect is to provide an optimization tailored by users’ requirements. This issue is solved by using a multicriteria optimization.

11. Conclusion

The dissertation thesis addresses the issue in the field of cloud computing. Nowadays, cloud computing is becoming one of the leading computing paradigm of parallel and distributed computing which has a potential to process huge amount of data [1, 16]. Significant IT companies such as Google, Amazon or Microsoft decided to build huge data centres providing cloud computing. Because of virtualization, physical nodes are transformed into virtual nodes which creates the illusion of infinite resources. This service is provided to a huge mass of customers through the Internet.

The thesis is focused on application performance optimization in multicloud environment. The issue is modelled as abstraction problem which the aim is to make optimization based on user’s requirement. It is a multicriteria optimization therefore. The user may, for example, require that their application completes the calculation in a particular time or use CPU and RAM optimally...

Based on state of the art, the thesis proposes the method which addresses the optimization task. The method is composed of the model of multicloud environment and taxonomy for multicriteria optimization. The optimization is carried out by a group of logical rules that allows the assessment of individual plans for the allocation of cloud resources upon which the most efficient plan is chosen. This approach allows effective handling of applications running in virtual machines.

Based on the model, the architectural design for the multicriteria optimization in multicloud environment was created. The approach has been subsequently verified and compared with similar approaches. The aim of the experiment was to provide a portal that offers a platform based on users’ needs.

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