



HAL
open science

Expression and Enforcement of Security Policy for Virtual Resource Allocation in IaaS Cloud

Yanhuang Li, Nora Cuppens-Boulahia, Jean-Michel Crom, Frédéric Cuppens,
Vincent Frey

► **To cite this version:**

Yanhuang Li, Nora Cuppens-Boulahia, Jean-Michel Crom, Frédéric Cuppens, Vincent Frey. Expression and Enforcement of Security Policy for Virtual Resource Allocation in IaaS Cloud. 31st IFIP International Information Security and Privacy Conference (SEC), May 2016, Ghent, Belgium. pp.105-118, 10.1007/978-3-319-33630-5_8. hal-01369546

HAL Id: hal-01369546

<https://inria.hal.science/hal-01369546>

Submitted on 21 Sep 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Expression and Enforcement of Security Policy for Virtual Resource Allocation in IaaS Cloud

Yanhuang Li^{1,2}, Nora Cuppens-Boulahia², Jean-Michel Crom¹,
Frédéric Cuppens², and Vincent Frey¹

¹ Orange Labs, 4 rue du Clos Courtel, 35510, Cesson-Sévigné, France

² Télécom Bretagne, 2 rue de la Châtaigneraie, 35510, Cesson-Sévigné, France
{yanhuang.li, jeanmichel.crom, vincent.frey}@orange.com
{nora.cuppens, frederic.cuppens}@telecom-bretagne.eu

Abstract. Many research works focus on the adoption of cloud infrastructure as a service (IaaS), where virtual machines (VM) are deployed on multiple cloud service providers (CSP). In terms of virtual resource allocation driven by security requirements, most of proposals take the aspect of cloud service customer (CSC) into account but do not address such requirements from CSP. Besides, it is a shared understanding that using a formal policy model to support the expression of security requirements can drastically ease the cloud resource management and conflict resolution. To address these theoretical limitations, our work is based on a formal model that applies organization-based access control (OrBAC) policy to IaaS resource allocation. In this paper, we first integrate the attribute-based security requirements in service level agreement (SLA) contract. After transformation, the security requirements are expressed by OrBAC rules and these rules are considered together with other non-security demands during the enforcement of resource allocation. We have implemented a prototype for VM scheduling in OpenStack-based multi-cloud environment and evaluated its performance.

Keywords: Cloud Security, Resource Management, Security Policy.

1 Introduction

Today cloud computing is essentially provider-centric. An increasing number of fiercely competing CSPs operate multiple heterogeneous clouds. In terms of IaaS, each provider offers its own, feature-rich solutions for customer VMs. More significantly, in cloud IaaS, physical hardware is usually shared by multiple virtual resources for maximizing utilization and reducing cost. Unfortunately, this vision suffers from a lack of homogeneity: many cloud virtual resources can not be deployed due to deficiencies in (1) unified expression; (2) interoperability. Lack of unified expression results in vendor lock-in: services are tightly coupled with the provider and depend on its willingness to deploy them. Lack of interoperability stems from heterogeneity of services, and more importantly of service-resource mapping, not compatible across providers. For better interoperability and control, cloud brokering is nowadays the rising approach towards

a user-centric vision. It may be seen as a paradigm in delivering cloud resources (e.g. compute, storage, network). With the help of brokering technology, user's security needs will be necessarily considered in cloud and these security requirements can be included in SLA contract which is a legal document where the service description is formally defined, delivered, and charged.

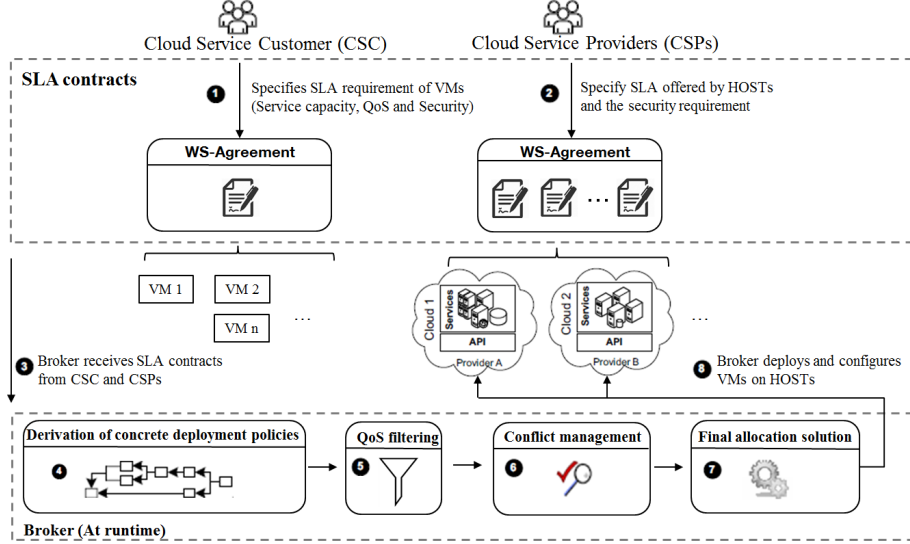


Fig. 1: The proposed policy based process to allocate virtual resources

Therefore, to overcome the aforementioned issues, we enhance the brokering technology by developing a configuration management process to allocate VMs in IaaS cloud. Shown in Figure 1, with WS-Agreement [1] based contracts, both CSC³ and CSP specify and manage their security requirements related to infrastructure in order to ensure end-to-end security across different components (Steps 1,2). After receiving the SLA contracts, the broker derives the concrete deployment policies according to security and non-security requirements (Steps 3,4,5). Particularly, the broker is able to arbitrate contradicting demands and make decisions (Step 6). In the end, the broker applies an algorithm to generate the final allocation solution (Step 7) then deploys and configures VMs on HOSTs (Step 8). Our method is evaluated by setting up a cloud computing environment to conduct virtual resource allocation process. Experimental results show that our approach demands minimal user (CSC and CSP)'s intervention and enables unskilled cloud users to have access to complex deployment scenarios. In particular, our solution tackles the lack of application of existing policy model that can support security expression when dealing with multiple clouds. Our contri-

³ In this paper, CSC stands for the end customer of cloud.

bution meets key-functional requirement for user-centric as (i) it addresses the SLA configuration options at the IaaS layer from service capacity to security constraint. (ii) it considers multiple requirements of security and applies the Or-BAC model to translate attribute-based security constraint to concrete policy. (iii) it provides conflict management to detect and handle the contradictory requirements from CSC and CSPs, with possibility to judge the policy priority by evaluating users' profiles. (iv) it proposes a resource allocation algorithm which takes resource capacity, QoS and security policy into account. To the best of our knowledge, there is no method in the literature that considers all these points.

The rest of the paper is organized as follows: Section 2 outlines the expression of security policy by CSC and CSPs with an exhaustive example. Section 3 illustrates the enforcement of security policy for VM allocation. Section 4 gives an implementation integrated with our solution and evaluates four experiments. Section 5 reviews existing proposals on cloud resource scheduling and security-aware allocation solution. Section 6 concludes the paper and outlines future work.

2 Expression of Security Policy

2.1 SLA Contract Expression

To generate security policies for CSC and CSP, we suggest, as a first step, to specify a generic document, which describes the requirements for service capacity, quality of service (QoS) and security constraint. SLA contract is such a document used in service negotiation and management. Based on a well-formatted template, CSP and CSC exchange their offers until reaching an agreement [2]. Among existing SLA specifications, we choose WS-Agreement because the format is open so that it can integrate various service parameters. Meanwhile, WS-Agreement is widely used by lots of research and industrial projects such as BREIN [3], IRMOS [4], and OPTIMIS [5]. Hence a WS-Agreement contract consists of name, context, service terms, guarantee terms and negotiation constraints, CSC and CSP can integrate service capacity, QoS and security requirement in its structure.

In cloud computing, the CSP's system can be viewed as a large pool of interconnected physical hosts. We use HOST to present the finite set of hosts from a CSP. Note that, VM and HOST may have multiple attributes each with their own values and these attributes can be assigned either manually by a user or automatically by the system. In terms of security requirement, as CSC and CSPs do not know the information of each other, they express their security constraints by attribute in Formulas 1, 2 and 3.

$$permission([H_{attr_name} : H_{attr_value}], [V_{attr_name} : V_{attr_value}]) \quad (1)$$

$$permission([H_{attr_name} : H_{attr_value}], [v_i]) \quad (2)$$

$$separate(v_i, v_j) \quad (3)$$

In the three formulas, H_{attr_name} and V_{attr_name} indicate the attribute name of HOST and VM respectively; H_{attr_value} and V_{attr_value} denote separately the attribute value of HOST and VM; each of v_i, v_j represents a unique virtual machine ID (VMID). Formulas 1 and 2 are used to specify the permission of VM allocation: HOST(s) with attributes assigned is (are) permitted to deploy VM(s). The difference is that in the first formula, the CSC specifies VM by attribute and in the second formula, VMID is given directly. These two options give the CSC more flexibility to express their security requirements. In addition, the CSC declares the coexistence constraint by Formula 3: v_i and v_j can not be allocated on the same HOST. Formula 4 is used by CSP to express the deployment prohibition. Similar with Formula 2, HOST with HOSTID h_i is not permitted to deploy VM(s) assigned with attribute.

$$prohibition([h_i], [V_{attr_name} : V_{attr_value}]) \quad (4)$$

In an example that we will use throughout the paper, we consider an DevOps [6] use case. DevOps is an emerged software development methodology that enhances collaboration between development, quality assurance (QA) and IT operations. Numerous companies are actively practicing DevOps since it aims to help them to maximize the predictability, efficiency, security, and maintainability of operational processes. Adoption of DevOps is being driven by many factors including using public IaaS. Suppose that a software company has to deploy 3 VMs (v_1, v_2, v_3) in cloud for a development project. Each VM contains its metadata such as properties, required volume, QoS specification and security constraint. We suppose that each VM runs a project server and there exist three types of VM: production (*prod*), development (*dev*), and test. *prod* server runs live applications supporting the company's daily business and the data is public for e-business customers; *dev* server consists of development environment thus developers with private right can access it; *test* server is used to conduct software test between development and production phase and it is accessible by testers with private login account. At the same time, there exist 2 CSPs (h_1, h_2) and each has its own metadata such as price, location and state indicating if it is certificated by security audit organizations. A readable illustration of VM and HOST configuration is shown in Figure 2.

2.2 Derivation of Security Policy

Security constraints need to be transformed to concrete security policies including VMID and HOSTID. Here we suggest using the OrBAC [7] model which supports the expression of permission and prohibition.

OrBAC in brief. The OrBAC model is an extension of the role-based access control (RBAC) [8] model. It defines a conceptual and industrial framework to meet the needs of information security and sensitive communication and allows

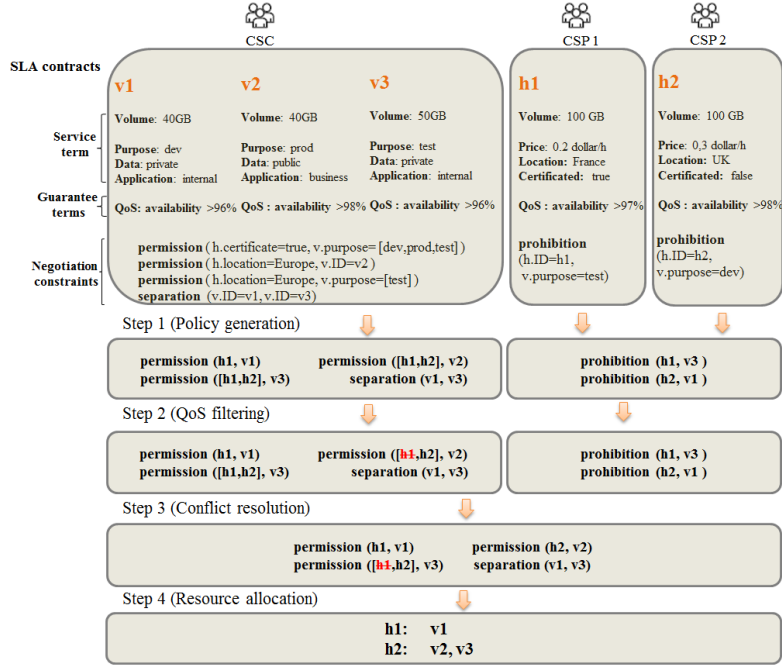


Fig. 2: An DevOps use case of virtual resource allocation

the policy designer to define a security policy independently. The concept of organization is fundamental in OrBAC. An organization is an active entity that is responsible for managing a security policy. Each security policy is defined for an organization. The model is not limited to permissions, but also includes the possibility to specify prohibitions and obligations. Besides, the security rules do not apply statically but their activation may depend on contextual conditions [9]. Context [10] is defined through logical rules and it can be combined in order to express conjunctive context, disjunctive context and negative context. An OrBAC policy is defined as: **security_rule (organization, role, activity, view, context)** where **security_rule** belongs to {permission, prohibition, obligation}. Once a security policy has been specified at the organizational level, it is possible to instantiate it by assigning concrete entities to abstract entities by the predicates which assign a subject to a role, an action to an activity and an object to a view. Meanwhile, all the operations are related to a specified context:

- *empower(org, subject, role)*: in organization org, subject is empowered in role;
- *consider(org, action, activity)*: in organization org, action implements activity;
- *use(org, object, view)*: in organization org, object is used in view;
- *hold(org, subject, action, object, context)*: in organization org, subject does action on object in context.

Based on the above definitions, a concrete permission policy could be derived by the following rule ⁴:

$$\begin{aligned}
& permission(org, role, activity, view, context) \\
& \wedge empower(org, subject, role) \wedge consider(org, action, activity) \\
& \wedge use(org, object, view) \wedge hold(org, subject, action, object, context) \\
& \rightarrow Is_Permitted(subject, action, object)
\end{aligned}$$

From security constraint to OrBAC policy. Derivation of OrBAC policy from security constraint requires policy mining technology which parses the configured rules and automatically reaches an instance of high level model corresponding to the deployed policy. Most of the existing RBAC based mining methods [11,12] generate abstract policy by taking concrete rules as input. However, in our scenario, both abstract and concrete rules should be derived from attribute-based description. The following is the problem definition.

Definition 1. *Policy Mining Problem*

Given a set of attribute of Subject S (HOST), a set of attribute of Action A , a set of attributes of Objects O (VM), and SAO_attr an attribute-based subject-action-object assignment relation (Formulas 1, 2, 4), find a set of ROLES, a subject-to-role assignment SR , a set of activity ACTIVITIES, an action-to-activity assignment AA , a set of VIEWS, an object-to-view assignment OV and $RAV \subseteq ROLES \times ACTIVITIES \times VIEWS$, a many-to-many mapping of role-to-activity-to-view assignment relation⁵.

Algorithm 1 explains the generation of permission policy. First of all, after receiving contracts from CSC and CSPs, broker extracts the attribute information of each VM and HOST then generates three kinds of structures as input: (1) VM list: storing all the attributes of related VMs; (2) HOST list: storing all the attributes of related HOSTs; (3) VM security constraint list: storing all the security constraints of CSC. After initialization of policy p , concrete action *deploy* is assigned to a new *activity* (lines 2,3). Then the relevant HOSTID list ID_h_list and relevant VMID list VM_v_list are generated from each term in VM security constraint list c_v (line 4-6). For example, the relevant HOSTID and VMID for the security constraint $permission(["certificate" : "true"], ["purpose" : "dev"])$ are HOST1 and VM1. After finding the relevant VMID(s) and HOSTID(s), an abstract permission with a new role *currentRole* and new view *currentView* is created (line 7-9). Finally, all the HOSTIDs in ID_h_list are assigned to *currentRole* and all the VMIDs in VM_v_list are assigned to *currentView* (line 10-15). The prohibition policy for CSP is generated in the same way by

⁴ A concrete prohibition policy $Is_Prohibited(subject, action, object)$ could be derived by the same way from $prohibition(org, role, activity, view, context)$.

⁵ In this paper, all the rules share the same action (“deploy”), organization (“superCloud”) and context (“default”). For reasons of simplicity, we do not illustrate organization and context in algorithm and policy.

taking input of VM list, HOST list and HOST security constraint list. Step 1 in Figure 2 demonstrates an example of permission and prohibition generation.

Algorithm 1 *permissionGeneration*(l_v, l_h, c_v): permission policy generation

Input: VM list l_v , HOST list l_h , VM security constraint list c_v

Output: OrBAC policy p

```

1: Initiate  $p$ 
2:  $p.activity \leftarrow$  create new activity
3:  $p.consider$ ("deploy",  $p.activity$ )
4: for  $c_{vi}$  in  $c_v$  do
5:    $ID_h.list \leftarrow$  get relevant HOSTID(s) from  $l_h$ 
6:    $ID_v.list \leftarrow$  get relevant VMID(s) from  $l_v$ 
7:    $p.currentRole \leftarrow$  create new role for HOSTs in  $ID_h.list$ 
8:    $p.currentView \leftarrow$  create new view for VMs in  $ID_v.list$ 
9:    $p_i \leftarrow$  create permission:  $permission(p.currentRole, p.activity, p.currentView)$ 
10:  for  $ID_{hi}$  in  $ID_h.list$  do
11:     $p.empower(ID_{hi}, p.currentRole)$ 
12:  end for
13:  for  $ID_{vi}$  in  $ID_v.list$  do
14:     $p.use(ID_{vi}, p.currentView)$ 
15:  end for
16: end for
17: return  $p$ 

```

3 Enforcement of Security Policy

3.1 QoS Filtering

Shown in Step 2 of Figure 2, this process aims to disable the permission which does not satisfy the QoS constraint. To this end, an evaluation between VM's performance requirements and HOST's capacity will be conducted. For example, in our scenario, QoS requirements contain the term of availability and the deployment permission between VM2 and HOST1 is disabled.

3.2 Conflict Management

After generating OrBAC policies from security constraint and executing QoS filtering, the broker aggregates permission rules of CSC and prohibition rules of CSP like:

$$permission(\{h_i\}, v_k) \quad (5)$$

$$prohibition(h_j, \{v_l\}) \quad (6)$$

In Formula 5, each VM v_k has a set of hosts $\{h_i\}$ which allow it to be deployed and in Formula 6, a set of VM $\{v_l\}$ are not permitted to deploy on the HOST h_j . The rewriting of rules is used to detect conflicts between permissions and prohibitions. A conflict corresponds to a situation where a subject HOST is both permitted and prohibited to perform a given action *deploy* on a given object VM. We divide conflicts into the following two types and for each type an allocation solution is proposed.

Type I: conflict with concession space. Defined in Formula 7, HOST h_j is permitted and prohibited simultaneously to deploy VM v_k . In fact, except for h_j , VM v_k has other allocation solutions. In this case, we disable h_j from the allocation permissions of v_k (Formula 8). For example, in step 3 of Figure 2, $permission(\{h_1, h_2\}, v_3)$ and $prohibition(h_1, v_3)$ belong to this type and the solution is disabling $permission(h_1, v_3)$.

$$\begin{aligned} conflict_TypeI(h_j, v_k) \leftarrow & permission(\{h_i\}, v_k) \wedge prohibition(h_j, \{v_l\}) \\ & \wedge h_j \in \{h_i\} \wedge v_k \in \{v_l\} \wedge (\{h_i\} \setminus h_j) \neq \phi \end{aligned} \quad (7)$$

$$disable(permission(h_j, v_k)) \leftarrow conflict_TypeI(h_j, v_k) \quad (8)$$

Type II: conflict without concession space. Shown in Formula 9, compared with the conflict of type I, the difference is that in Type II, except for h_i , VM v_k has no other deployment solutions. In this case, we adopt a priority based approach proposed in [13] and introduce two labels $p(h)$ and $p(v)$ as priorities of VM and HOST. $p_1 \prec p_2$ means that p_2 has higher priority than p_1 . As virtual resource allocation is related to different factors such as risk and trust, the priorities could be predefined by users or determined by the broker. For example, some of CSPs' prohibitions can be disabled by the broker in case that the CSC has a low risk score. Making decisions on priority is beyond the scope of this paper and here we suppose that CSPs obtain higher priority to fulfill all their security requirements. Thus, in Formula 10, the current conflict resolution is disabling the permission of h_i . For example, the solution for $permission(h_3, v_1)$ and $prohibition(h_3, v_1)$ is disabling the former rule.

$$\begin{aligned} conflict_TypeII(h_i, v_k) \leftarrow & permission(h_i, v_k) \wedge prohibition(h_j, \{v_l\}) \\ & \wedge h_i = h_j \wedge v_k \in \{v_l\} \end{aligned} \quad (9)$$

$$disable(permission(h_i, v_k)) \leftarrow conflict_TypeII(h_i, v_k) \wedge p(v_k) \prec p(h_i) \quad (10)$$

3.3 Virtual Resource Allocation

The aim of previous steps is to generate the final VM allocation solution. Without loss of generality, we demonstrate the generation of allocation solution from security policy by considering the CSC's preference on price. Algorithm 2 shows

the resource allocation process. It takes permission policy p , VM list l_v , HOST list l_h and separation constraint c as input and generates the deployment solution which maps VMs to HOSTs. In each permission rule, VMID and a list of its possible target HOSTs are extracted (line 1-4). To satisfy the price preference of CSC, the target HOSTs are ranked from low price to high price (line 5) thus the one with the lower price will be chosen preferentially. The final deployment solution depends on mainly two factors (line 9): (1) if the VM has coexistence conflict with the VMs which have been already deployed on the HOST. (2) if the HOST has enough volume to deploy the VM. Step 4 in Figure 2 shows an example of resource allocation.

Algorithm 2 *resourceAllocation*(p, l_v, l_h, c): virtual machine allocation

Input: OrBAC permission p , VM list l_v , HOST list l_h , separation constraint c

Output: deployment solution

```

1: for each concrete rule  $r_i$  in  $p$  do
2:   if  $r_i$  is active then
3:      $ID_{vi} \leftarrow$  get object in  $r_i$ 
4:      $ID\_h\_list \leftarrow$  get all the HOSTIDs permitted for  $ID_{vi}$  in  $r_i$ 
5:     Rank  $ID\_h\_list$  from low price to high price
6:     for  $ID_{hj}$  in  $ID\_h\_list$  do
7:        $v_i \leftarrow$  get VM from  $l_v$  by  $ID_{vi}$ 
8:        $h_j \leftarrow$  get HOST from  $l_h$  by  $ID_{hj}$ 
9:       if  $ID_{vi}$  not in separation constraint  $c$ 
10:        and  $h_j$  has enough volume for  $v_i$ 
11:        and  $v_i$  has not been allocated then
12:          add ( $v_i$  attaches host  $h_j$ ) to  $solution$ 
13:        end if
14:      end for
15:   end for
16: return  $solution$ 

```

4 Implementation and Evaluation

SUPERCLOUD [14] is a European project which aims to support user-centric deployments across multi-cloud and enable the composition of innovative trustworthy services. Its main objective is to build a security management architecture and infrastructure to fulfill the vision of user-centric secure and dependable clouds of clouds. One use case is developing a middle-ware layer between CSC and CSPs and this middle-ware could allocate virtual resources on physical infrastructures. In this context, there is a need to consider a multi-cloud environment with security constraints. For example, virtual resources should not be mapped to physical resources that do not comply with its security requirements; physical

eration) once contracts are processed by the broker. In Figure 5, we study the amount of time the broker takes to generate security policies with increasing number of VM and HOST. For example, 60 as values in x-axis and y-axis indicates that there exist 60 VMs and HOSTs and the corresponding value in z-axis (400ms) shows the short time needed to generate the OrBAC policies.

4.3 Experiment 3: allocation latency

Our third experiment investigates the impact of VM number and HOST number on the execution time of Algorithm 2. In Figure 6, VM and HOST number vary from 10 to 60. Given 60 as VM and HOST number, the allocation latency takes about only 1 second. In real case, as HOST number is limited, the estimation of allocation latency is acceptable and it confirms the efficiency of our resource allocation algorithm.

4.4 Experiment 4: price

The experiment measures the cost for CSC after VM allocation. We generate VMs randomly from 10 to 60 and configure 8 HOSTs. For simplicity, each HOST is supposed to provide only one type of IaaS solution with price fixed from 0.02 dollars/hour to 0.08 dollars/hour⁶. Then we compare the total price between two allocation solutions. The first solution is Algorithm 2 which concerns CSC's price preference and the second solution does not consider it thus VMs are allocated arbitrary on HOSTs. As a result, Algorithm 2 shows a great advantage in reducing the deployment cost.

5 Related Work

Although virtual resource scheduling problems are NP-complete, it is well-studied by the research community by proposing various heuristic and approximate approaches for addressing different issues. Among three service models (SaaS, PaaS and IaaS) of cloud computing, virtual resource allocation in IaaS cloud has been considered by some works in the literature. Some of these works [20,21] focus on the capacity of CSP. In this case, some strategies like immediate, best effort and Nash equilibrium [22] have been applied to allocation algorithm in order to optimize the deployment algorithm with constraints such as QoS and energy [23]. Another effort is SLA-oriented resource management [24]. Among lots of requirements of CSC, security is a critical issue to be taken into account [25]. Bernsmed et al. [26] present a security SLA framework for cloud computing to help potential CSCs to identify necessary protection mechanisms and facilitate

⁶ The prices are inspired from current cloud IaaS solution of Amazon EC2 and Microsoft Azure. For example, in Amazon EC2, price for the instance of m4.xlarge (4 cores, 16G RAM) is 0.239\$/h and it costs 0.308\$/h (4 cores, 7G RAM) for the instance of A3 in Microsoft Azure.

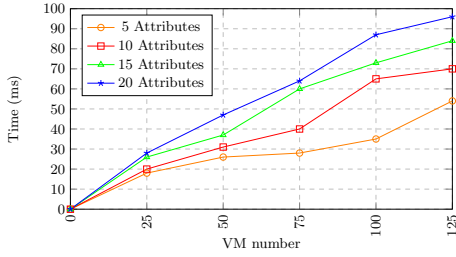


Fig. 4: Time for contract processing

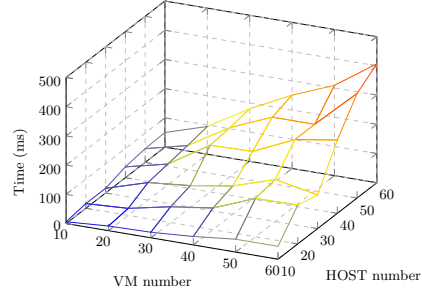


Fig. 5: Time for policy generation

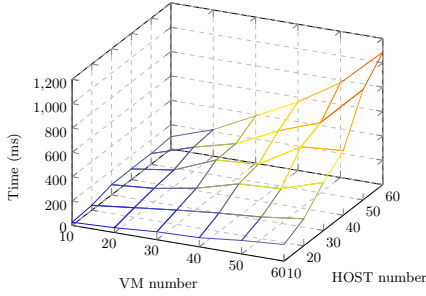


Fig. 6: Latency for VM allocation

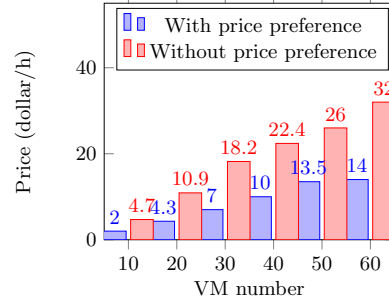


Fig. 7: Total price for VM allocation

automatic service composition. Berger et al. [27] take isolation constraint and integrity guarantee into consideration and implement controlled access to network storage based on security labels. In [28], different virtual resource orchestration constraints are resumed and expressed by attribute-based paradigm. Regarding these constraints, a conflict-free strategy is developed to mitigate risks in IaaS Cloud [29]. Most of above works have been motivated from security requirements expressed by CSC. In [30], CSP specifies its security requirements including forbid constraint which forbids a set of VM instances from being allocated on a specified HOST. However, in multi-cloud environment, as CSC and CSPs do not have vision of each other before establishing contract, specifying security requirement can be very tricky for both sides. The main focus of these efforts is scheduling VMs either for the purpose of high-performance computing or satisfying security constraints according to the requirements of CSC. Our approach is to capture security and non-security requirement from both CSC and CSP, and apply a formal policy model to drive virtual resource allocation.

6 Conclusion

In this paper, we have presented, formalized and enforced security requirement for virtual resource allocation. We first present the SLA contracts for CSC and

CSPs which contain service capacity, QoS and security constraint. We then transform the attribute-based SLA contract to concrete OrBAC policies. Finally, we allocate virtual resources after resolving conflicts in policies and demonstrate the efficiency and reliability of our solution by OpenStack-based implementation.

In future works, we plan to investigate the decision making during the conflict resolution. Another potential direction is to develop a suitable front-end application interface for SLA contract specification.

Acknowledgments. The work reported in this paper has been supported by ANRT (Association Nationale de la Recherche et de la Technologie) and Orange as a CIFRE (Conventions Industrielles de Formation par la REcherche) thesis and the work of Nora Cuppens-Boualahia and Frédéric Cuppens has been partially carried out in the SUPERCLOUD project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 643964.

References

1. Andrieux, A., Czajkowski, K., Dan, A., Keahey, K., Ludwig, H., Nakata, T., Pruyne, J., Rofrano, J., Tuecke, S., Xu, M.: Web services agreement specification (ws-agreement). In: Open Grid Forum. Volume 128. (2007) 216
2. Li, Y., Cuppens-Boualahia, N., Crom, J.M., Cuppens, F., Frey, V.: Reaching agreement in security policy negotiation. In: Trust, Security and Privacy in Computing and Communications (TrustCom), 2014 IEEE 13th International Conference on, IEEE (2014) 98–105
3. Muñoz, H., Kotsiopoulos, I., Micsik, A., Koller, B., Mora, J.: Flexible sla negotiation using semantic annotations. In: Service-Oriented Computing. IC-SOC/ServiceWave 2009 Workshops, Springer (2010) 165–175
4. <http://www.irmosproject.eu/>
5. Ziegler, W., Jiang, M., Konstanteli, K.: Optimis sla framework and term languages for slas in cloud environment. OPTIMIS Project Deliverable D 2 (2011)
6. <http://en.wikipedia.org/wiki/DevOps>
7. Kalam, A.A.E., Baida, R., Balbiani, P., Benferhat, S., Cuppens, F., Deswarte, Y., Mieke, A., Saurel, C., Trouessin, G.: Organization based access control. In: Policies for Distributed Systems and Networks, 2003. Proceedings. POLICY 2003. IEEE 4th International Workshop on, IEEE (2003) 120–131
8. Sandhu, R.S., Coyne, E.J., Feinstein, H.L., Youman, C.E.: Role-based access control models. *Computer* (2) (1996) 38–47
9. Cuppens, F., Cuppens-Boualahia, N.: Modeling contextual security policies. *International Journal of Information Security* 7(4) (2008) 285–305
10. Coma, C., Cuppens-Boualahia, N., Cuppens, F., Cavalli, A.R.: Context ontology for secure interoperability. In: Availability, Reliability and Security, 2008. ARES 08. Third International Conference on, IEEE (2008) 821–827
11. Vaidya, J., Atluri, V., Guo, Q.: The role mining problem: finding a minimal descriptive set of roles. In: Proceedings of the 12th ACM symposium on Access control models and technologies, ACM (2007) 175–184

12. Hachana, S., Cuppens-Bouahia, N., Cuppens, F.: Mining a high level access control policy in a network with multiple firewalls. *Journal of Information Security and Applications* **20** (2015) 61–73
13. Cuppens, F., Cuppens-Bouahia, N., Ghorbel, M.B.: High level conflict management strategies in advanced access control models. *Electronic Notes in Theoretical Computer Science* **186** (2007) 3–26
14. <http://www.supercloud-project.eu/>
15. Fernando M. V. Ramos, N.N.: Preliminary architecture of the multi-cloud network virtualization infrastructure. Technical report (2015)
16. <http://docs.openstack.org/developer/devstack/>
17. <https://www.openstack.org/>
18. Autrel, F., Cuppens, F., Cuppens-Bouahia, N., Coma, C.: Motorbac 2: a security policy tool. In: 3rd Conference on Security in Network Architectures and Information Systems (SAR-SSI 2008), Loctudy, France. (2008) 273–288
19. <http://en.wikipedia.org/wiki/JSON>
20. Ferreira Leite, A., Alves, V., Nunes Rodrigues, G., Tadonki, C., Eisenbeis, C., Magalhaes Alves de Melo, A.C.: Automating resource selection and configuration in inter-clouds through a software product line method. In: Cloud Computing (CLOUD), 2015 IEEE 8th International Conference on, IEEE (2015) 726–733
21. Nathani, A., Chaudhary, S., Somani, G.: Policy based resource allocation in iaas cloud. *Future Generation Computer Systems* **28**(1) (2012) 94–103
22. Wei, G., Vasilakos, A.V., Zheng, Y., Xiong, N.: A game-theoretic method of fair resource allocation for cloud computing services. *The journal of supercomputing* **54**(2) (2010) 252–269
23. Beloglazov, A., Abawajy, J., Buyya, R.: Energy-aware resource allocation heuristics for efficient management of data centers for cloud computing. *Future generation computer systems* **28**(5) (2012) 755–768
24. Buyya, R., Garg, S.K., Calheiros, R.N.: Sla-oriented resource provisioning for cloud computing: Challenges, architecture, and solutions. In: Cloud and Service Computing (CSC), 2011 International Conference on, IEEE (2011) 1–10
25. Li, Y., Cuppens-Bouahia, N., Crom, J.M., Cuppens, F., Frey, V., Ji, X.: Similarity measure for security policies in service provider selection. In: *Information Systems Security*. Springer (2015) 227–242
26. Bernsmed, K., Jaatun, M.G., Undheim, A.: Security in service level agreements for cloud computing. In: CLOSER. (2011) 636–642
27. Berger, S., Cáceres, R., Goldman, K., Pendarakis, D., Perez, R., Rao, J.R., Rom, E., Sailer, R., Schildhauer, W., Srinivasan, D., et al.: Security for the cloud infrastructure: Trusted virtual data center implementation. *IBM Journal of Research and Development* **53**(4) (2009) 6–1
28. Bijon, K., Krishnan, R., Sandhu, R.: Virtual resource orchestration constraints in cloud infrastructure as a service. In: *Proceedings of the 5th ACM Conference on Data and Application Security and Privacy*, ACM (2015) 183–194
29. Bijon, K., Krishnan, R., Sandhu, R.: Mitigating multi-tenancy risks in iaas cloud through constraints-driven virtual resource scheduling. In: *Proceedings of the 20th ACM Symposium on Access Control Models and Technologies*, ACM (2015) 63–74
30. Jhavar, R., Piuri, V., Samarati, P.: Supporting security requirements for resource management in cloud computing. In: *Computational Science and Engineering (CSE), 2012 IEEE 15th International Conference on, IEEE (2012) 170–177*