Open access • Journal Article • DOI:10.1007/S10723-018-9449-Z

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Published on: 01 Mar 2019 - Journal of Grid Computing (Springer Netherlands)

Topics: Cloud computing, Computer cluster, Live migration, Virtual machine and Virtualization

Multi-Elastic Datacenters: Auto-Scaled Virtual Clusters on Energy-Aware Physical Infrastructures

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Abstract

Computer clusters are widely used platforms to execute different computational workloads. Indeed, the advent of virtualization and Cloud computing has paved the way to deploy virtual elastic clusters on top of Cloud infrastructures, which are typically backed by physical computing clusters. In turn, the advances in Green computing have fostered the ability to dynamically power on the nodes of physical clusters as required. Therefore, this paper introduces an open-source framework to deploy elastic virtual clusters running on elastic physical clusters where the computing capabilities of the virtual clusters are dynamically changed to satisfy both the user application's computing requirements and to minimise the amount of energy consumed by the underlying physical cluster that supports an on-premises Cloud. For that, we integrate: i) an elasticity manager both at the infrastructure level (power management) and at the virtual infrastructure level (horizontal elasticity); ii) an automatic Virtual Machine (VM) consolidation agent that reduces the amount of powered on physical nodes using live migration and iii) a vertical elasticity manager to dynamically and transparently change the memory allocated to VMs, thus fostering enhanced consolidation. A case study based on real datasets executed over a production infrastructure is used to validate the proposed solution. The results show that a multi-elastic virtualized datacenter provides users with the ability to deploy customized scalable computing clusters while reducing its energy footprint.

Keywords: Cloud Computing, Green computing, Elasticity

1. Introduction

Computer clusters are a very common computing facility used both for scientific institutions and enterprises. A cluster consists of a set of computing nodes connected using at least one high-speed low-latency network and it is usually managed by a Local Resource Management System (LRMS) used to manage the whole lifecycle of the jobs.

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These jobs typically represent different workloads such as High Throughput Computing (HTC) or High Performance Computing (HPC).

However, physical clusters face several drawbacks. Firstly, they require a significant capital investment together with the costs required for housing and periodic hardware maintenance. Secondly, maintaining a physical cluster up and running on a 24/7 basis in order to deliver full level of service, when it is required, is very expensive, mainly due to the cost of energy [15]. Indeed, the energy is consumed both by the cluster itself and the cooling system required to maintain the environmental conditions. These physical clusters are typically over-dimensioned to cope with increased workloads and, specially, peaks of demand. However, these peaks are rarely reached while underutilization is a very often scenario. Indeed, as Williams et al. [40] described, in well-provisioned datacenters, overload is unpredictable, relatively rare, uncorrelated, and transient.

Therefore, one of the challenges for computing clusters is to reduce their energy consumption. The energy saving techniques applied for clusters are basically, Static Power Management (SPM) techniques, which consist of using more efficient components, and Dynamic Power Management (DPM) techniques, that consist of adapting the infrastructure to the actual workload [37]. One common DPM approach for computing clusters is to power off those physical nodes that are idle and power them back on again as they are needed. Such energy saving technique has been proved to provide substantial cost reduction in cluster infrastructures in our previous publication [16].

On the other hand, user applications typically have special requirements (libraries, compilers, Operating System (OS) versions, etc.) what leads to potential software conflicts on multi-tenant scenarios where multiple users share the same cluster. Also, virtualization and Cloud Computing have changed the way of managing a datacenter. Many datacenters are creating their on-premises Clouds to manage their servers using a Cloud Management Platform (CMP) such as OpenNebula, OpenStack, VMWare vCenter, etc. Then, the sysadmins create the Virtual Machines (VMs) needed by the users instead of granting access to physical machines. Indeed, Virtual Cluster (VC) use VMs as the computing nodes, which can support the same functionality as their physical counterparts. This way, virtual clusters can be specifically tailored to the hardware, software and configuration requirements of applications to be run on them. The ability to provision customized virtual clusters is beneficial both for the user, who can access computing resources on-demand and for the sysadmin, since these clusters are decoupled from the underlying execution infrastructure and no adaptation of applications to the computing environment is required.

Indeed, users are provided customized virtual clusters running an specific version of an OS and a set of libraries, managed by the preferred LRMS of the user. Providing VCs with a precise hardware and software configuration that matches the requirements of an application better guarantees its successful execution. VCs are provisioned on-demand and terminated when no longer required so that other virtual clusters can be deployed, thus providing the means of multiplexing access to the underlying physical computing resources. Virtual clusters can also benefit from the elasticity of Cloud infrastructure by terminating the idle VMs and provisioning new ones when they are needed. These Elastic Virtual Clusters (EVC) behave as physical clusters where the DPM technique is applied to the cluster to power on or off the nodes. In the case of the EVC, the working nodes are VMs that are deployed or terminated depending on the workload.

However, such dynamism in the creation and destruction of VMs in an on-premises

Cloud typically leads to a fragmented distribution of the VMs in the physical servers. In this situation, the request to deploy a VM can be denied because no single host has enough physical resources, even though the aggregation of physical resources from different nodes would allow the VM to be deployed. Increasing the consolidation ratio, where VMs are hosted in a fewer number of hosts, would allow the deployment of the VM. Moreover, the physical Cloud platform can also benefit from the aforementioned DPM technique to power off idle servers in order to reduce the overall energy consumption of the on-premises Cloud.

This paper describes the work towards a multi-elastic datacenter in which the users are delivered EVCs that run on top of on-premises Cloud infrastructures supported by elastic energy-aware physical clusters. The physical nodes that are not hosting any VMs are automatically powered on or off, as needed, to introduce elasticity at a physical level. The VMs of the EVC can be vertically scaled, in terms of the allocated memory, according to the dynamic memory consumption patterns of the application (or applications) being executed. These VMs are automatically live-migrated between hosts to increase server consolidation and use a reduced number of physical hosts. Therefore, this creates a multi-elastic datacenter where automated horizontal elasticity is applied for physical and virtual computing resources together with automated vertical elasticity for the EVCs. A set of open-source developments have been released in order to support this vision and deployed in production within our research group.

After the introduction, the paper is organized as follows. First, section 2 discusses the related work in the different areas covered by this paper. Next, section 3 describes the proposed approach together with the building blocks required to build a multi-elastic datacenter. Later, section 4 describes a case study in order to assess the advantages of the proposed approach. Finally, section 5 summarises the paper and points to future work.

2. Related work

Apart from the CMP, that manages the lifecycle of VMs running on the aforementioned physical infrastructure, several key components are needed for the multi-elastic datacenter: i) a tool to deploy customized EVCs through VMs managed by the aforementioned CMP and ii) an automated power management system for the physical infrastructure; iii) mechanisms to consolidate the VMs in the CMP in order to increase the VM-per-host ratio; iv) a system to automatically change the memory allocation of the VMs to the dynamic requirements of the applications being executed on them. The following subsections describe the main related works in these areas.

2.1. Elastic Virtual Clusters

There are different examples of tools to deploy virtual clusters in the literature, such as [10], [18] or [39]. These works mainly deal with the provision of the VMs and configuration of the cluster topology (e.g. connectivity, shared filesystem, ssh-ability, etc.). Some of them include configuration capabilities (e.g. installing applications, creating users, etc.). However, their approach lacks elasticity. In this sense, once a cluster has been delivered to the user, all the VMs will continue running even if they are idle. Such static behaviour may prevent from creating new clusters because of the lack of resources.

Focusing on elastic clusters, there are several works that address the problem. As an example, [17] and [26] evaluate the possibility of using Amazon EC2 to extend a physical cluster, depending on the workload. In [31], the authors explore the dynamic provision of working nodes in the cloud, depending on the size of the jobs in the queues, introducing several policies to limit the amount of working nodes to be powered on. The main limitation of these works is that they seem to be ad-hoc private implementations that have not been released as open-source components.

Focusing on ready-to-use open-source tools, the standard distribution of Hadoop [5] includes an easy-to-use mechanism to create a virtual cluster in Amazon Web Services (AWS). The main problem is that is exclusively designed for Hadoop and, in addition, the number of nodes for the cluster is not dynamically managed (although it is possible to manually add or destroy working nodes). StarCluster [29] is an open source cluster-computing toolkit built exclusively for AWS. It uses pre-built Virtual Machine Images (VMI) with specific software installed. It is based on the Open Grid Scheduler LRMS (formerly known as SGE) and includes common libraries such as OpenMPI, OpenBLAS, Lapack, etc. It also features a module called Elastic Load Balancer that supports shrinking or expanding the cluster based on the statistics of the queues of the LRMS. However, the cluster is not self-managed since an external system (typically the user's computer running the StarCluster application) has to monitor the cluster to decide whether elasticity should be performed.

In this way, [3] is a development to create entire virtual clusters running a batch system such as HTCondor that grow and shrink automatically based on the usage, although this requires external continuous monitoring of the cluster. The caveat in this work is that it can only run their Virtual Machine Images, and requires a Cloud platform compliant with the Amazon EC2 interface.

As opposed to previous works, we propose a system that builds entirely on publicly available open-source components in order to automatically manage elasticity both at the physical and the virtual levels, featuring vertical elasticity for virtual clusters. These features, combined with dynamic power management of physical clusters and automated consolidation of VMs via live migration provides the foundation of a multi-elastic datacenter. As far the authors are aware there is no such approach currently available in the literature that addresses simultaneous multi-level elasticity of virtual infrastructures on physical infrastructures.

2.2. Automated Power Management

The main CMPs do not offer automated power management out of the box, specially in the open-source versions of the products. For example, OpenQRM[1] introduces power saving features exclusively for the enterprise version, which is distributed under a commercial license. In the commercial cloud platforms, there are several solutions that offer automated power management features. This is the case of VMWare vSphere 5.5[2] which is capable of powering on and off physical hosts. However, it is restricted to the VMWare's hypervisor in addition to being very costly (beginning at USD 2,875.00 for the version able to manage the power of the nodes). Huawei's FusionSphere[3] also offers

[1] http://www.openqrm-enterprise.com
[2] http://www.vmware.com/products/vsphere
[3] http://e.huawei.com/en/products/cloud-computing-dc/cloud-computing/fusionsphere/fusionsphere

automated power management. It builds up on OpenStack, but its solution is also distributed under a commercial license. However, commercial solutions are out of the scope of this paper since once purchased a commercial CMP, the user is typically restricted to the solutions offered by the specific vendor.

2.3. Facilitating Power Management

There are works that try to reduce the number of physical servers needed to host the VMs deployed on a Cloud, specially at the scheduler level. In fact, most of the schedulers shipped in the default distributions of the CMPs include features for reducing the number of used servers. However, during the lifecycle of the platform (i.e. sequences of creation and destruction of VMs) the distribution of the VMs may prevent from achieving idle servers even when the running VMs could be hosted in a fewer number of servers.

There are several works that try to profit from live-migration features to consolidate the VMs in a platform into a few number of physical hosts. Some common approaches consist of applying reinforcement learning [33][11][19], fuzzy logic [28] or nature-based solutions such as the works in [20] (which is inspired on the movements of the ants in a colony), [32] and [27] (that are inspired on the behaviour of the swarms during migratory flights), or [21] (which is based on the movements of a bee colony). Other approach consist of modelling the problem as a *multidimensional bin packing* (mBP) problem where the physical nodes are modelled as multi-dimensional containers, and each dimension corresponds to a resource (typically CPU, memory or hard disk). In this field there are several proposal of works such as [2] that statically reduces the number of physical hosts, but is not intended to be used in a continuously working platform.The work by Verma et al. [38] tries to combine VM placement with Dynamic Voltage and Frequency Scaling (DVFS). Finally, it is noticeable the work by Beloglazov et al. [4] that solves the bin packing problem and includes a scheduler to take into account energy saving criteria to re-place the VMs, or the works [22] and [34] that also try to reduce the number of used physical hosts.

2.4. Adapting the VMs to the actual workload

The users tend to overestimate the amount of memory required by their applications resulting in unused memory that could be dedicated to additional VMs running on the same physical machine [36]. Moreover, CMPs typically offer different instance types, also known as *flavours* in the case of OpenStack, out of which the VMs are instantiated. These instance types define the amount of memory, cores and storage that will be allocated to the VM. The users select the instance type according to its constraints (e.g. the number of cores) even if they do not need the corresponding amount of memory. Apart from the waste of resources, over-dimensioning a VM also hinders VM consolidation into a reduced number of servers.

Some works have tried to adjust the resources of the VMs to the actual workload. As an example, the work shown in [12] tries to adapt the allocation of the CPU in the VMs running on the Xen hypervisor, but it does not consider changing the memory. There are also other works such as [35] and [23] that try to adapt the virtual memory to the actual needs of the applications running in the VMs using various methods. However, they consider it only at the host level instead of the whole physical infrastructure managed by the CMP. Therefore, the CMP is not able to oversubscribe the hosts considering the

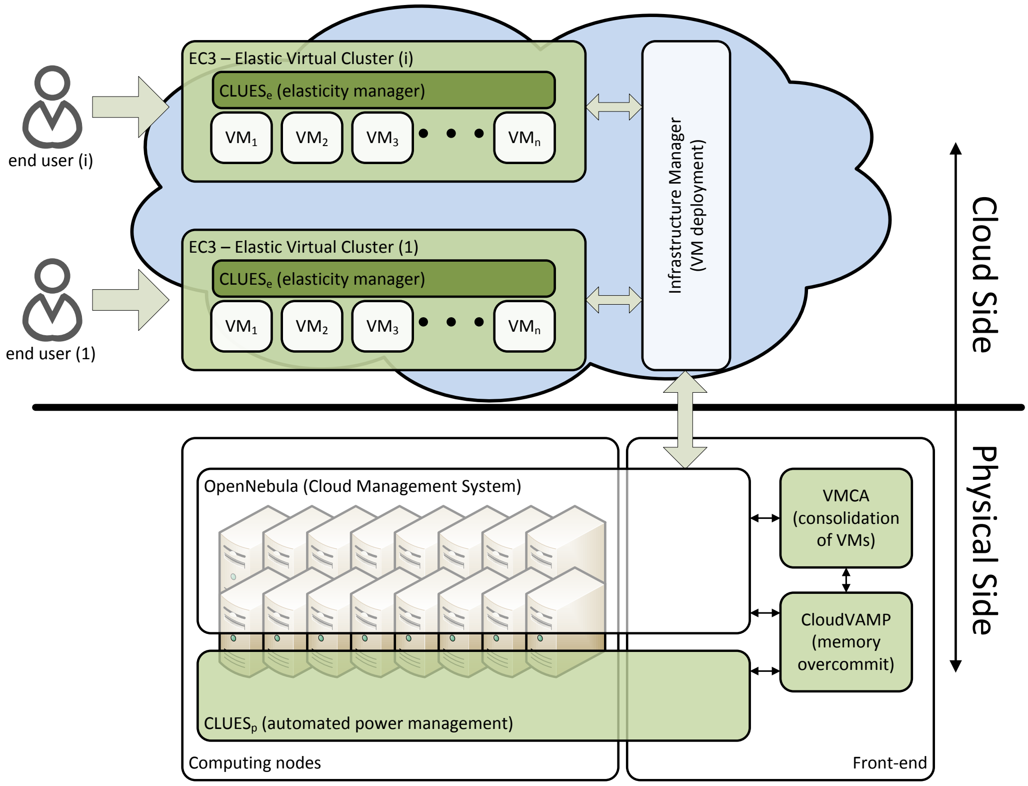


Figure 1: The multi-elastic datacenter building blocks.

memory that is actually being used rather than the memory that is currently allocated. There are also works such as [25] that tackle the problem at the CMP level, but their approach does not provide countermeasures in case the host memory is overcommitted and a VM claims back the memory that it had originally requested.

3. The Multi-Elastic Datacenter

The building blocks of the multi-elastic datacenter are summarized in Figure 1. Two layers are clearly distinguished: the Cloud Infrastructure (Physical Side) and the Cloud Services & Application (Cloud Side). On the one hand, the Cloud infrastructure is managed by the system administrators who are responsible for installing and managing both the physical servers and the CMP. On the other hand, the Cloud Services & Application layer provides the user with the EVCs on which applications/jobs are executed.

3.1. The Cloud Infrastructure Layer

The Cloud infrastructure comprises a set of physical servers arranged as an on-premises Cloud platform and managed by a CMP such as OpenNebula or OpenStack.

The following components have to be installed by the system administrator to introduce the ability of dynamic power management, i.e., elasticity at the physical level:

- *CLUster Energy Saving (CLUES)*[4] [14] which is an automated power manager for computer clusters. It also supports plugins to integrate with CMPs such as OpenNebula, in order to power on and off the physical nodes depending on the requirements. For physical computer clusters, CLUES monitors the LRMS to decide when additional worker nodes have to be powered on according to different reactive policies. For virtual clusters, the semantics of powering on and off the nodes have been changed into deployment and termination of VMs. This way, CLUES can dynamically provision and relinquish VMs from a Cloud provider. For CMPs, CLUES intercepts the VM deployment requests to decide if physical nodes should be powered on. Using the same framework for elasticity at those three levels enable to reuse policies and maintain a consistent behaviour across the different layers.
- *Virtual Machine Consolidation Agent (VMCA) [13]*[5] starts from an existing VM distribution within an on-premises Cloud and produces a migration plan in order to achieve a set of idle nodes for CLUES to power them off. Live migrations are performed with the support provided by the KVM hypervisor and it has been integrated with the OpenNebula CMP.
- *Cloud Virtual Machine Automatic Memory Procurement (CloudVAMP)*[6] [30] is an automatic system that enables and manages memory over-subscription in an on-premises OpenNebula Cloud platforms. Using active monitoring of the VMs and considering the actual memory used by the VM, regardless of the initially allocated memory, it dynamically resizes the memory of the running VMs without downtime by leveraging memory ballooning techniques provided by the KVM hypervisor. Fully integrated with the CMP, it lets OpenNebula deploy additional VMs per server thus increasing the VM-per-host ratio and, as a side product, letting VMCA to obtain more idle servers. Live migration is employed to prevent memory overload of the physical hosts in order to restore the level of service.

The interface between the Cloud infrastructure and the Cloud services & application is the CMP. Apart from the common administrative tasks in the platform (e.g. creating OS disks, managing users and permissions, creating subnetworks, etc.), the interaction from the Cloud consists of creating or destroying VMs. The events that may happen in the physical side as a result from the creation or destruction of VMs are described below:

- When new VMs are created and there are not enough resources (typically in terms of memory or number of virtual CPUs) for them, $CLUES_p$ will power on one or more physical nodes to provide the required resources to run the new VMs. The VMs deployment request are held by the CMP until the physical servers are powered on. When the physical nodes are finally available, the VMs are deployed, and they will be started by the CMP on the appropriate host(s).

[4]CLUES - `http://www.grycap.upv.es/clues`
[5]VMCA - `http://www.grycap.upv.es/vmca/`
[6]CloudVAMP - `http://www.grycap.upv.es/cloudvamp`

- When physical servers become idle, either because the VMs terminate or VMCA has migrated them to other physical nodes, $CLUES_p$ will power them off to save energy.

- If a VM j is not using the memory requested during its creation, CloudVAMP will dynamically reduce its allocated memory without any downtime for the VM, according to the vertical elasticity rules described in [30].

- If a VM j whose memory was reduced requires it, e.g. the application running on the VM starts demanding more memory, CloudVAMP will check if the server in which it is hosted has enough free physical memory. If not, CloudVAMP will request $CLUES_p$ to power on a new physical server, and once the server is available, the VM will be live migrated to it. Once the VM is in a host that has enough free physical memory, CloudVAMP will increase the memory of the VM, according to the vertical elasticity rules.

- If some VMs are in a physical host h_t but they can be hosted among other servers without compromising the quality of service, VMCA will prepare and execute a migration plan to get the host h_t free. Once the VMs are migrated, $CLUES_p$ will power off the physical node, since the host h_t became idle.

3.2. The Cloud Services & Applications Layer

Users deploy their EVCs by means of EC3 (Elastic Cloud Computing Cluster)[7] [9]. This is a tool to deploy self-managed cost-efficient elastic virtual clusters on top of Cloud platforms. It supports different LRMS such as SLURM, Torque, Mesos and SGE. EC3 relies on the Infrastructure Manager[8] [7] to provision the VMs on multiple back-ends, including, but not limited to, public Clouds such as Amazon Web Services and on-premises Clouds such as OpenNebula and OpenStack. EC3 deploys a front-end node with CLUES specifically configured to be able to deploy and terminate VMs, instead of dealing with physical hosts. This is called $CLUES_e$ in Figure 1. This way, when additional worker nodes are required, new VMs are automatically deployed up to a user-specified maximum on the Cloud platform. It also includes support for hybrid deployments across multiple Clouds (either on-premises and/or public), migration capabilities and automatic checkpointing together with cost-efficient mechanisms such as the usage of spot instances, a potentially cost-reducing instance type available in Amazon EC2.

Once the user has deployed an EVC i, some events will happen on this layer:

- When the user submits new jobs to the cluster, $CLUES_e^i$ will check if there are enough free working nodes to execute the job. If this is not the case and the maximum cluster size has not been reached, it will ask the IM to deploy additional VMs to be integrated as new working nodes in the cluster in the LRMS. Notice that this procedure is transparent to the user, who only notices a delay since the time the job is submitted to the LRMS and the time the job starts executing.

- When the working nodes become idle for a while, $CLUES_e^i$ will terminate the corresponding VMs in order to free the used computing resources.

[7]EC3 - `http://www.grycap.upv.es/ec3`
[8]IM - `http://www.grycap.upv.es/im`

CLUES support multiple customizable elasticity rules, described deeply in [14]. As an example, CLUES can be configured to power on single nodes or groups of nodes based on a sensor system, and power them off when they are idle a configuring period of time.

3.3. Complex actions in the Multi-Elastic Datacenter

During the lifecycle of the multi-elastic datacenter, some complex actions may be triggered as a result of the interaction of the user with the clusters in the Cloud. These complex actions are the result of the interaction of the different building blocks of the multi-elastic data center. Examples of such actions are summarized below:

- A user submits a job to cluster i. $CLUES_e^i$ detects that there are not free working nodes and requests a VM to the IM. The IM deploys a new VM through the CMP. $CLUES_p$ detects that there are not free physical servers and powers on a new one. When the physical host is on, the VM is started and the IM can integrate the VM in the cluster i. The job can finally be started. Again, this process is completely transparent for the user.
- A VM which is part of the cluster i is not using the memory requested. CloudVAMP reduces the size of the memory of the VM. The VM is alone in one of the physical servers, but VMCA detects that it can fit into other server. Therefore, VMCA live-migrates the VM, and now the physical host is idle. If the server is still idle after for a certain amount of time, $CLUES_p$ powers off the physical server.
- A VM (VM_j^i) whose memory was downsized, in the cluster i, starts using the memory again. CloudVAMP detects that there is not enough allocated physical memory in the server in which the VM is hosted and requests $CLUES_p$ to power on a new physical server. When the physical server is available, CloudVAMP live-migrates VM_j^i to the new server and resizes the granted memory.

All the aforementioned components are distributed as open-source and made available in GitHub[9]. Additionally, some of the components have been adopted in large-scale research infrastructures. In particular, the IM has been integrated in the VMOps Dashboard of EGI (European Grid Infrastructure), see [6] for details, while EC3 has been integrated in the EGI Access service to provide Virtual Elastic Clusters as a Service for the Long Tail of Science (LToS), see [8] for details.

4. Case Study

This section describes a case study in order to validate the proposed solution to produce multi-elastic datacenters on realistic settings. For this, we adopted real workloads obtained form the Grid Workloads Archive [24] and considered an scenario where two virtual elastic clusters were deployed by means of EC3 on the same Cloud infrastructure configured with the aforementioned tools. Both clusters executed the same job submission pattern. The second virtual cluster (C2) was created three hours after the first one (C1). The maximum size of each virtual cluster was fixed to 12 nodes, considering the

[9]GitHub Organization: `https://github.com/grycap`

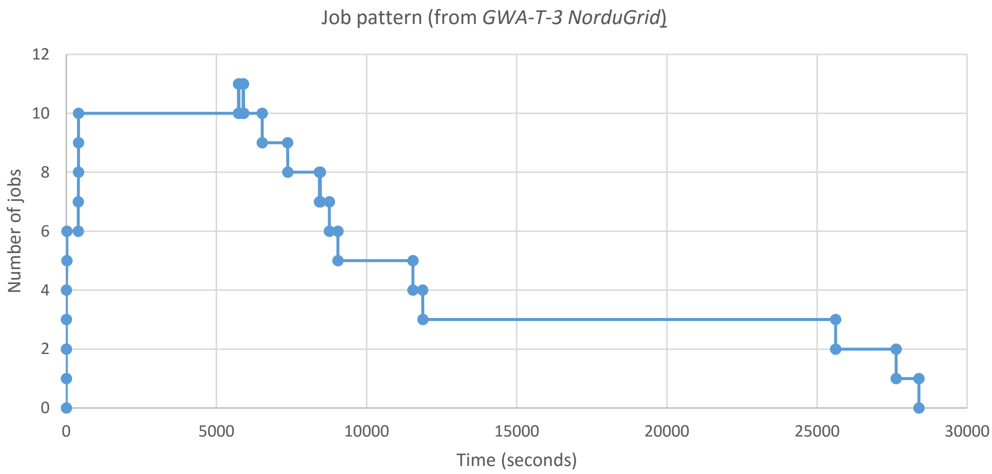


Figure 2: Workload of the case study, extracted from the *GWA-T-3 NorduGrid* dataset. The blue line represents the evolution of the workload in terms of number of jobs.

workload used. The following configuration was specified for $CLUES_e$, i.e., the elasticity manager of the virtual clusters: i) no limit to the number of nodes concurrently provisioned and ii) idle nodes where powered off after 600 seconds.

The underlying physical infrastructure employed is used in production and during the execution of the case study, $CLUES_p$, i.e., the energy-aware elasticity manager, did not have to power on physical nodes on which the VMs of the virtual clusters would be running. Notice that the only effect in the case study would be an increased time since a VM is deployed until the VM is up and running to include the time required to power on the physical node.

Concerning memory ballooning, CloudVAMP was configured to keep a minimum memory size per VM of 384 MB, required for the Operating System to properly function and allowing each node to maintain a 30% of free memory, which corresponds to a Memory Overprovisioning Percentage (MOP) slightly increased compared to the 20% value used in our earlier work in vertical elasticity [30]. Indeed, for this case study, the amount of cluster reconfigurations caused by adding additional nodes to the clusters introduced additional memory usage peaks which were better accommodated by these increased free memory safety margin.

The real workload, used in both cluster executions, is a fragment extracted from the *GWA-T-3 NorduGrid* dataset offered by the Grid Workloads Archive (from line 4 to line 16 of the *.gwf* file), and represented in Figure 2 in terms of number of jobs. For the sake of reproducibility of results, the duration of each job has been reduced up to a 200%. The jobs executed in that dataset are 13 sequential tasks [1], with an average duration of 186 min. In our case, we used a synthetic memory-consuming application[10] that is able to reproduce a pattern of memory usage that consists of three periods, (i) increasing from 0

[10]https://github.com/grycap/synthalloc

MB to 500 MB, (ii) maintaining the consumption in those 500 MB of memory, and (iii) reducing the usage of memory from 500Mb to 0 Mb. This behaviour can be appreciated in Figure 3, where the granted memory for a node of the cluster C1 is represented. The rationale behind the pattern is to use a dynamic memory consumption pattern in order to trigger the activation of CloudVAMP for the adjustment of the allocated memory to the VMs.

FiXme Note: @Carlos/@Migue: revisad si los datos de onecloud son correctos.

The underlying physical infrastructure used is composed by an heterogeneous blade-based system that has four kind of nodes: 2 x (2 quad-core L5430@2.6 Ghz, 16 GB), 2 x (2 quad-core multithreaded E5520@2.26 GHz, 16 GB), 6 x (2 quad-core multithreaded E5620@2.4 GHz, 16 GB) and 3 x (4 quad-core multithreaded E7520@1.86 GHz, 64 GB), with a total amount of 128 cores and 352 GB of RAM. The blade system is backed by a 16 TB SAN connected via a private gigabit ethernet network. This system is managed by OpenNebula 5.2.1, using KVM as the underlying hypervisor.

For the deployment of the virtual cluster nodes we have relied on pre-configured VMIs, since these introduces a 70% savings of time in the contextualization phase for each virtual node[9]. Therefore, the VMI selected is based on Ubuntu 14.04 with SLURM 14.11 and NFS pre-installed. Each VM, that corresponds with a node of the cluster, has been deployed with one CPU and requesting 1024 Mb of RAM memory.

Finally, the effects of VMCA were not analysed in this case study since the focus is set on the multi-level elasticity achieved by the integration of a vertical elasticity memory oversubscription tool (CloudVAMP) with a horizontal elasticity manager (CLUES) for the execution of applications with dynamic memory-consuming patterns on virtual elastic clusters. A detailed analysis of VMCA is published in [13].

4.1. Results

In this subsection, we first analyse the results obtained from the execution, and then discuss the main contributions of the proposed solution. Figures 3 and 4 cover the main results of the case study.

Figure 3 shows the evolution of the granted memory for a VM of cluster C1. The orange line represents the three different memory consuming phases of the application, as described above, during its execution. Every job has a different duration execution time. The grey line of the graph represents the granted memory to the VM while the blue line represents the initially requested memory of the VM (1024 MB). Indeed, the memory requested when deploying the VM represents an upper bound to the memory allocated at any given time to the VM.

Notice in the figure that a newly deployed VM receives all the requested memory (1024 MB), but as soon as CloudVAMP detects that the VM has free memory beyond the thresholds set by the 30% MOP, it steals the unused memory in order to make room in the physical node for other VMs to be deployed on that node by the OpenNebula scheduler. The amount of memory borrowed never leaves the VM with less than 384 MB of RAM and less that 30% of free memory.

The spiky peaks in the granted memory to the VM (gray line) appear to be related to memory consumption by other applications running inside the VM, specially concerning the horizontal elasticity of the virtual cluster, i.e. when the whole cluster is reconfigured by Ansible when a new virtual node is deployed or a virtual node is terminated because no jobs are available for execution.

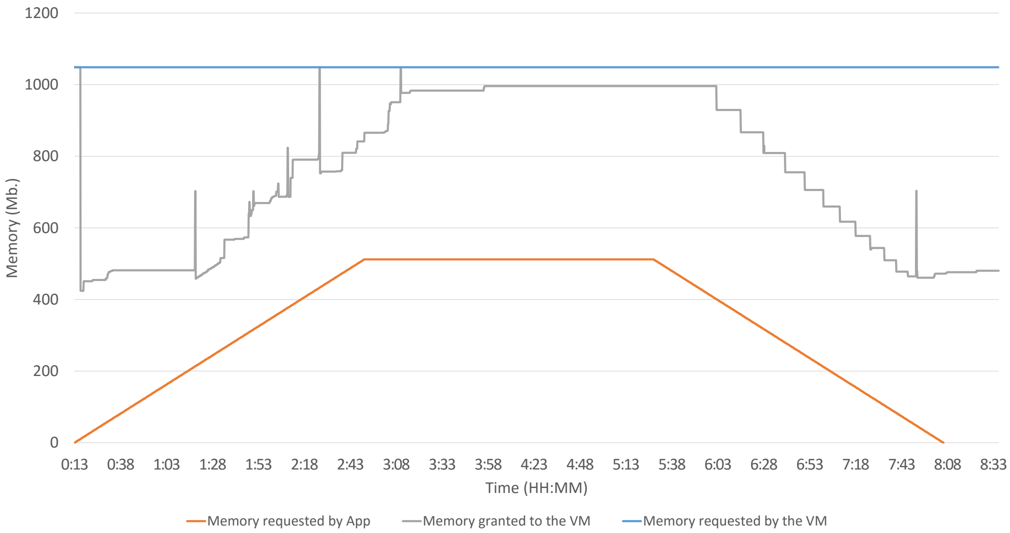


Figure 3: Granted memory of a working node from cluster C1 in contrast with the job requested memory. The orange line represents the memory requested by the job. The grey line represents the memory granted to the VM while the blue line depicts the initial memory requested by the VM.

Finally, the figure shows the grace period (600 s.) that CLUES allocated to the idle virtual node, before terminating it, just in case further jobs were submitted to be deployed in that cluster. This strategy enables to gently accommodate an incoming job without requiring an additional deployment of a virtual node, at the expense of an increased energy consumption in the underlying physical infrastructure. Notice that this grace period can be configured by the user.

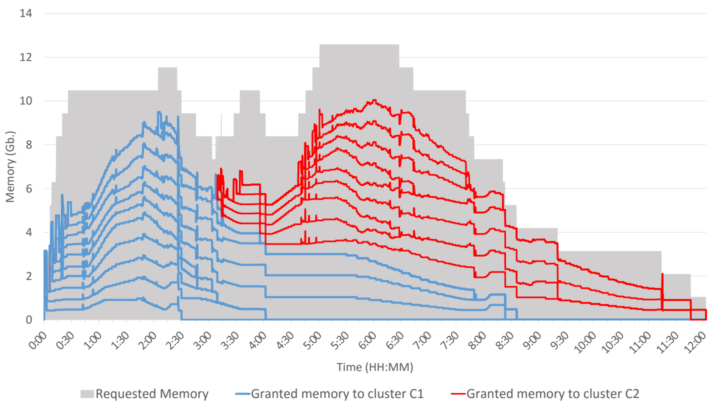
Figure 4 describes the evolution of the total requested memory and the memory granted to the different virtual nodes of the two clusters (Figure 4(a)) and the evolution of the size of the clusters in terms of number of nodes, i.e. VMs (Figure 4(b)).

Figure 4(a) differentiates the results for cluster C1, where each blue line represents the granted memory to each node of the cluster, and for cluster C2, where red lines are used. The light grey area in the background represents the total memory assigned for both clusters during the execution, managed by CloudVAMP. This tool was able to dynamically and transparently change the memory allocated to VMs depending on the current workload. Its effect can be noticed when comparing the grey area with the blue and red lines, where the first represents the total memory initially requested by each VM that compose the clusters (which was 1024 Mb per node) and the second the real assigned memory to each VM

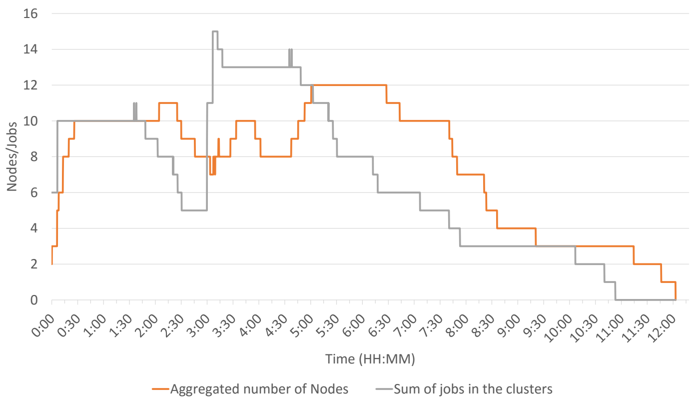
FiXme Note: Amanda, esta ultima frase no la entiendo.

Specifically, CloudVAMP introduced a 29.13% memory saving, thus allowing increased server consolidation ratio and, thus, better usage of resources.

Figure 4(b) shows the elasticity evolution of both clusters, C1 and C2, in terms of number of nodes. The size of both clusters was dynamically adapted to their current workload by CLUES, a fact that can be appreciated comparing the grey lines (the aggregated job submission pattern for both clusters) and orange (aggregated number of nodes



(a) Evolution of the total memory consumption.



(b) Evolution of size of the clusters considering the workload pattern.

Figure 4: Performance evaluation of the proposed scenario for the complete execution.

for clusters C1 and C2). An appreciable delay between both lines in the graph depicts the time needed for the VMs to be deployed and configured to be integrated as a new a node of each virtual cluster, i.e., the contextualization process. This introduces a delay in the execution of jobs unless an idle node is available in the cluster, an scenario that occurred in both clusters for the last three jobs of the workload. This is the reason why the size of both clusters do not achieve the maximum number of concurrent jobs depicted in the graph close to time instante 3:00.

5. Conclusions and further work

This paper has introduced open-source components to manage multi-elastic datacenters, where elastic virtual clusters run on top of elastic energy-aware physical clusters. This way, the computing capabilities of the virtual clusters are dynamically changed to satisfy both the user application's computing requirements and to reduce the amount of energy consumed by the underlying physical cluster that supports an on-premises

Cloud. For these, both horizontal elasticity, to add or remove nodes of the virtual cluster to adjust to the workload, and vertical elasticity techniques, to dynamically change the memory allocation of the VMs, have been combined. These developments can be adopted as an integrated approach to achieve better resource usage without requiring any additional effort by the users, which use the virtual computing clusters as if they were physical ones.

Future work involves addressing the dynamic allocation of CPUs for each VM, a feature that could not be initially developed due to the lack of support by the KVM hypervisor in which we based our development for CloudVAMP. OpenNebula has added support for *cgroups* in cooperating with KVM, thus paving the way for further research in this area. Also, the components will be evolved to support Container Orchestration Platforms instead of Cloud Management Platforms, where challenges in the area of integrated vertical and horizontal elasticity require further research activity.

Acknowledgements

The authors would like to thank the Spanish "Ministerio de Economía, Industria y Competitividad" for the project "BigCLOE' under grant reference TIN2016-79951-R.

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