Workload trace generation for dynamic environments in cloud computing

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Abstract—Cloud computing datacenters provide millions of virtual machines in actual cloud markets. In this context, Virtual Machine Placement (VMP) is one of the most challenging problems in cloud infrastructure management, considering the large number of possible optimization criteria and different formulations that could be studied. In the existing literature, the VMP problem is mostly formulated as a provider-oriented VMP considering static (offline) or dynamic (online) formulations. Considering the on-demand model of cloud computing, the VMP problem should be optimized dynamically to efficiently attend typical workload of modern applications. This work proposes a novel taxonomy in order to understand possible challenges for Cloud Service Providers (CSPs) in dynamic environments, based on the most relevant dynamic parameters studied so far in the VMP literature. The identified challenges must be addressed in future formulations and novel algorithms for an efficient utilization of resources in real world cloud computing datacenters and for a further advance of this important research area.

1. PROPOSED TAXONOMY

A. Cloud Service Notation

Formally, a cloud service $S_b$ can be distributed across different possible cloud datacenters. Each cloud datacenter $DC_c$ hosts VMs $V_{bcj}$ associated to different cloud services. A VM $V_{bcj}$ associated to $S_b$ is denoted as $V_{bcj}''$. Where:

- $S_b$: Cloud service $b$;
- $DC_c$: Cloud datacenter $c$;
- $mDC_c$: Number of VMs $V_{c}$ in $DC_c$;
- $mS_b$: Number of VMs $V_{j}$ in $S_b$;
- $V_{j}'$: $V_{j}$ in $DC_c$;
- $V_{bcj}'$: $V_{bcj}$ in $DC_c$ from service $S_b$.

B. Dynamic Environment Notation

In this work, different environments represent particular types of requests for placement of cloud services from the CSPs’ perspective. According to the proposed taxonomy, 16 different possible dynamic environments could be identified considering one or more of the following classification criteria: (1) horizontal elasticity, (2) vertical elasticity, (3) overbooking of server resources and (4) overbooking of network resources.

Additionally to the notation presented in Section 1.A, each cloud datacenter $DC_c$ is defined as:

$$ DC_c = \{V_{c1}', V_{c2}', \ldots, V_{cm_c}'\} \quad (1) $$

where:

- $DC_c$: Cloud datacenter $c$;
- $V_{c}'$: $V_{c}$ in $DC_c$;
- $mDC_c$: Number of VMs $V_{c}'$ in $DC_c$.

Each VM hosted at each cloud datacenter $DC_c$ that corresponds to cloud service $S_b$ is denoted as $V_{bcj}'$. For simplicity this work consider only processing, memory and network resources for a VM, but the notation is general enough for considering any set of virtual resources.

$$ V_{bcj}' = \{V_{bcj}''_{cpu}, V_{bcj}''_{ram}, V_{bcj}''_{net}, R_{bcj}''_{net}, SLA_{bcj}''_{cpu}, t_{init}, t_{end}\} \quad (2) $$

where:

- $V_{bcj}''$: $V_{bcj}$ in $DC_c$ from service $S_b$;
- $V_{bcj}''_{cpu}$: Processing requirements of $V_{bcj}'$ in [ECU];
- $V_{bcj}''_{ram}$: Memory requirements of $V_{bcj}'$ in [GB];
- $V_{bcj}''_{net}$: Network requirements of $V_{bcj}'$ in [Mbps];
- $R_{bcj}''_{net}$: Economical revenue for locating $V_{bcj}'$ in [$\$];
- $SLA_{bcj}''_{cpu}$: SLA of $V_{bcj}'$. $SLA_{bcj}''_{cpu} \in \{1, \ldots, s\}$;
- $t_{init}$: Initial instant where $V_{bcj}'$ is executed;
- $t_{end}$: Final instant where $V_{bcj}'$ is executed.

The utilization of the resources of each $V_{bcj}'$ is defined as:

$$ U_{bcj}' = \{U_{bcj}''_{cpu}, U_{bcj}''_{ram}, U_{bcj}''_{net}\} \quad (3) $$

where:

- $U_{bcj}''_{cpu}$: Utilization of requirements of $V_{bcj}'$;
- $U_{bcj}''_{ram}$: Utilization of $V_{bcj}''_{ram}$ in [ECU];
- $U_{bcj}''_{net}$: Utilization of $V_{bcj}''_{net}$ in [GB];
- $U_{bcj}''_{net}$: Utilization of $V_{bcj}''_{net}$ in [Mbps].

Each of the 16 different identified environments considers different parameters that dynamically change in function of...
time $t$, representing different notation for each environment. The following subsections detail each of the identified dynamic environments, presenting particular notation for its characterization.

C. Dynamic Environment Classification

Based on the notation presented in Section II.B the 16 identified environments present particular considerations and different time variables are defined for its characterization. A summary of the time variables is presented in Table II.

D. Dynamic Environment Examples

This section will show representative examples with a briefly explanation of the 16 different dynamic environments.

An example of the most basic environment for solving online formulations of the provider-oriented VMP problem (Environment 1) is presented in Figure 1. The mentioned example represents the request of cloud services $S_1$ (in blue) and $S_2$ (in brown), which are distributed across cloud datacenters $DC_1$ and $DC_2$ from $t = 0$ to $t = 5$.

Figure 1 presents different levels of detail for the environment. The trace level represents the requests that CSPs receive for the placement of cloud services (or VMs) in the PMs of the available cloud datacenters. Next, cloud service levels ($S_1$ and $S_2$) detail requested resources of cloud services on each time slot.

The request for allocation of $S_1$ arrived at $t = 0$ and finished at $t = 4$, while $S_2$ requested resources from $t = 2$ to $t = 5$. Finally, cloud datacenter levels ($DC_1$ and $DC_2$) detail requested resources of cloud services for each cloud datacenter.

Figure 2 represents overbooking of server resources (Environment 2) and it shows the variation of memory utilization (in orange) and CPU utilization (in violet) from $t = 0$ to $t = 5$ of $V_{111}$. The trace level maintains the number of virtual machine and no variation over CPU and RAM along the time slot taking into account that this scenario do not consider horizontal and vertical elasticity.

Figure 3 (Environment 3) shows an example of dynamic utilization of virtual network resources (in green) along time $t$. The dynamic utilization of both virtual server and network resources of $V_{111}$ is shown in Figure 4 representing environment 4. Analogously to the environment 2, environment 3 and 4 do not consider vertical and horizontal elasticity.

An example of an environment with horizontal elasticity (Environment 5) for scaling up and down the number of VMs associated to a cloud service $S_1$ to efficiently attend the dynamic demand of resources is presented in Figure 5.

Initially, cloud service $S_1$ starts in $t = 0$ requesting 2 VMs (in blue) across cloud datacenters $DC_1$ and $DC_2$. Assuming an increasing demand for resources $S_1$ scale up the number of VMs adding 1 VM in cloud datacenter $DC_1$ (in brown) in $t = 1$. In $t = 2$, $S_1$ scale up the number of VMs adding 1 VM in cloud datacenter $DC_2$ (in brown) resulting in 4 VMs for attending the demand from $t = 2$ to $t = 3$. The cloud service $S_1$ returns to its initial configuration scaling down to 2 VMs in $t = 4$ assuming a decreasing demand for resources, finishing the request for resources at $t = 5$.

Overbooking of server resources could be also considered with horizontal elasticity, as shown in Figure 6 (Environment 6). This example shows the utilization of server resources of $V_{111}$ in order to represent how resource utilization could vary in one (or more) VM in a period of time during horizontal elasticity.

Analogously to the Environment 6, Figure 7 represents the utilization of dynamic network resources of $V_{111}$ in the Environment 7 along $t = 0$ and $t = 5$ considering horizontal elasticity.

At Figure 8 (Environment 8), both dynamic server and network resources are considered for a safe overbooking on each time slot.

A dynamic environment that contemplates vertical elasticity is exposed on Figure 9 representing the Environment 9. This example considers processing (in pink) and memory (in dark blue) requirements associated to the virtual resources capacities of $V_{111}$ from $t = 0$ to $t = 5$.

For this particular environment, additionally to vertical elasticity, dynamic utilization of virtual server resources is shown in Figure 10 to represent Environment 10.

Analogously to the environment mentioned before (Environment 10), Figure 11 shows the Environment 11 with a dynamic utilization of virtual network resources of $V_{111}$ and vertical elasticity.

Figure 12 shows the particular environment that jointly considers overbooking of server and network resources of $V_{111}$ in a time slot with vertical elasticity as an example of the Environment 12.

According to the Table II the Environment 13 jointly considers horizontal and vertical elasticity. This scenario is shown in Figure 13 with the variation of the number of VMs and the consideration of the resource requirements of $V_{111}$ (as an example) from $t = 0$ to $t = 5$.

Besides to horizontal and vertical elasticity, Figure 14 shows the dynamic utilization of server resources of $V_{111}$ on environment 14.

Equally to environment 14, Figure 15 (Environment 15), exposed dynamic utilization of network resources of $V_{111}$ with vertical and horizontal elasticity.

Finally, this last complex dynamic scenario shown in Figure 16 considers both types of overbooking and both types of elasticity (Environment 16).

E. Workload Trace Generation Example

As an example of utilization of the mentioned workload trace generator, Table II presents the input data considered for the generation of the workload trace presented in Table ??.

II. WORKLOAD TRACES FOR DYNAMIC ENVIRONMENTS

Considering that several research opportunities that have been identified from the different dynamic environments proposed in this work, sample workload traces for each particular environment are required in order to explore the challenges
associated to each environment, propose formulations and test algorithms that solve these challenges with different workload types and effectively compare performance and quality of different algorithms with reproducible experiments.

As identified in [1], there is no existing tests problem instances for the VMP that could be used as a world accepted benchmark. Consequently, the authors are working on a workload trace generator for the VMP problem to be able to generate different instances for experimental tests based on the dynamic environments proposed in this work. A brief introduction of preliminary results is presented in this section.

The proposed workload trace generator for the VMP problem actually considers the following input data: (1) workload trace duration, (2) range of values for virtual resources of VMs, (3) range of values for utilization of virtual resources of VMs, (4) range of values of revenue for executing VMs, (5) range of values of SLA of VMs, (6) range of number of VMs of cloud services, (7) number of cloud services and (8) data probability distribution. It is remarkable that additionally, the user is also able to include real world workload traces, extending or reducing the trace to specific requirements for the experiments.

A. Workload Trace Generation Example

As an example of utilization of the mentioned workload trace generator, Table II presents the input data considered for the generation of the workloads traces that will be presented in this section.

Table III is an example of the most basic dynamic environment identified in this work (Environment 1). This is an example where VMs were created and removed without considering overbooking and elasticity. The number of VMs scales down from 2 (at \( t = 0 \)) to 1 (at \( t = 2 \)). Then, the number of VMs scale up from 1 (at \( t = 3 \)) to 2 (at \( t = 4 \)) where a new VM was created.

For environment 2, the Table IV is formulated considering overbooking of server resources without considering elasticity. Therefore, it can be observed that \( Ucpu_{111} \) scales up from 4 [ECU] (at \( t = 0 \)) to 5 [ECU] (at \( t = 1 \)) and \( Uram_{111} \) scales up from 14 [GB] (at \( t = 0 \)) to 15 [GB] (at \( t = 1 \)).

Analogously to Table [V] Table [V] do not consider elasticity. Environment 3 presents network resource overbooking.

| ID | Elasticity Type | Overbooking Type | Time Variables |
|----|----------------|-----------------|----------------|
| 1  | Not Considered | Not Considered | -              |
| 2  | Not Considered | Server          | \(-Ucpu_{111}^{'}(t)\) \(-Uram_{111}^{'}(t)\) |
| 3  | Not Considered | Network         | \(-Unet_{111}^{'}(t)\) |
| 4  | Not Considered | Server and Network | \(-Ucpu_{111}^{'}(t)\) \(-Uram_{111}^{'}(t)\) \(-Unet_{111}^{'}(t)\) |
| 5  | Horizontal | Not Considered | \(-mS_b(t)\) |
| 6  | Horizontal | Server          | \(-mS_b(t)\) \(-Ucpu_{111}^{'}(t)\) \(-Uram_{111}^{'}(t)\) |
| 7  | Horizontal | Network         | \(-mS_b(t)\) \(-Unet_{111}^{'}(t)\) |
| 8  | Horizontal | Server and Network | \(-mS_b(t)\) \(-Ucpu_{111}^{'}(t)\) \(-Uram_{111}^{'}(t)\) \(-Unet_{111}^{'}(t)\) |
| 9  | Vertical | Not Considered | \(-Vcpu_{111}^{'}(t)\) \(-Vram_{111}^{'}(t)\) |
| 10 | Vertical | Server          | \(-Vcpu_{111}^{'}(t)\) \(-Vram_{111}^{'}(t)\) \(-Ucpu_{111}^{'}(t)\) \(-Uram_{111}^{'}(t)\) |
| 11 | Vertical | Network         | \(-Vcpu_{111}^{'}(t)\) \(-Vram_{111}^{'}(t)\) \(-Unet_{111}^{'}(t)\) |
| 12 | Vertical | Server and Network | \(-Vcpu_{111}^{'}(t)\) \(-Vram_{111}^{'}(t)\) \(-Ucpu_{111}^{'}(t)\) \(-Uram_{111}^{'}(t)\) |
| 13 | Horizontal and Vertical | Not Considered | \(-mS_b(t)\) \(-Vcpu_{111}^{'}(t)\) \(-Vram_{111}^{'}(t)\) |
| 14 | Horizontal and Vertical | Server          | \(-mS_b(t)\) \(-Vcpu_{111}^{'}(t)\) \(-Vram_{111}^{'}(t)\) \(-Ucpu_{111}^{'}(t)\) \(-Uram_{111}^{'}(t)\) |
| 15 | Horizontal and Vertical | Network         | \(-mS_b(t)\) \(-Vcpu_{111}^{'}(t)\) \(-Vram_{111}^{'}(t)\) \(-Unet_{111}^{'}(t)\) |
| 16 | Horizontal and Vertical | Server and Network | \(-mS_b(t)\) \(-Vcpu_{111}^{'}(t)\) \(-Vram_{111}^{'}(t)\) \(-Ucpu_{111}^{'}(t)\) \(-Uram_{111}^{'}(t)\) \(-Unet_{111}^{'}(t)\) |

Table I

| Input Data | Value (Min, Max) |
|------------|------------------|
| Workload trace duration (t) | (4,4) |
| Range of values resources of CPU | (1,10) |
| Range of values resources of Memory | (0.5,52) |
| Range of values resources of Network | (100,10000) |
| Range of values utilization CPU | (1,10) |
| Range of values utilization Network | (0.5,52) |
| Range of values utilization Memory | (0,10000) |
| Range of values of revenue executing VMs | (0.1,1.5) |
| Range of values SLA of VMs | (0,6) |
| Number of VMs of cloud services | (2,6) |
| Number of cloud services | (1,1) |
| Data probability distribution | Random |

Table II

| SUMMARY OF TIME VARIABLES FOR 16 DYNAMIC ENVIRONMENTS. |
For the following environment, Environment 6, Table VIII shows horizontal elasticity (VMs scale up and down) in addition to server resource overbooking. The dynamic utilization is shown in $U_{cpu}$ and $U_{ram}$ columns from $t = 0$ to $t = 4$.

Network resource overbooking with horizontal elasticity is exposed in Table IX (Environment 7). Analogously to Table VIII this table shows the dynamic utilization of network resources from $t = 0$ to $t = 4$ at $U_{net}$ column.

Table X shows Environment 8. This table considers horizontal elasticity with network and server resources. The variation of the resources ($U_{cpu}$, $U_{ram}$ and $U_{net}$) in this table shows the dynamism of this scenario.

A dynamic environment that considers vertical elasticity and no overbooking is shown in Table XI. Vertical elasticity for processing resources could be observed in this workload trace (Environment 9) from $t = 3$ to $t = 4$, where $V_{cpu}''_{111}$ and $V_{cpu}''_{121}$ decrease from $8$ [ECU] to $4$ [ECU], assuming a decreasing demand of resources.

Vertical elasticity and server resources overbooking is shown in Table XII. Vertical elasticity is shown from $t = 0$ to $t = 4$ in this table and the dynamism of server resources is exposed in $U_{cpu}$ and $U_{ram}$ columns.

Analogously to Environment 10 (Table XII), Table XIII shows vertical elasticity with dynamic utilization of network resources in $U_{net}$ along the period of time $t = 0$ to $t = 4$.

Table XIV shows vertical elasticity with server and network resources. For this particular environment, $U_{cpu}$ and $U_{ram}$ shows the variability of the utilization that a machine could take during a period of time.

Horizontal and vertical elasticity with no overbooking can be observed in the workload trace of Table XV (Environment 13). Horizontal elasticity is shown with the scale up and down of VMs from time $t = 0$ to $t = 4$. Vertical elasticity for processing resources is shown with the variability of $V_{cpu}$ and $V_{ram}$.

Environment 14 is represented in Table XVI. It shows horizontal and vertical elasticity with server resource overbooking. Server resource is shown in $U_{cpu}$ and $U_{ram}$ column from $t = 0$ to $t = 4$.

Analogously to environment 14, Table XVII (Environment 15) shows horizontal and vertical elasticity with the consideration of dynamic utilization of network resources and could be seen along $t = 0$ to $t = 4$ on $U_{net}$.

Table XVIII represents a basic example of the most complex dynamic environment identified in this work (Environment 16). This example includes all possible dynamic parameters (resource capacities of VMs, number of VMs of a cloud service and utilization of resources of VMs).

Horizontal elasticity is considered in Table XVIII in order to efficiently attend the increasing demand of resources scaling up the number of VMs of $S_1$ from 2 (at $t = 0$) to 3 (at $t = 1$) and from 3 (at $t = 1$) to 4 (at $t = 2$). The number of VMs scales down from 4 (at $t = 3$) to 2 (at $t = 4$), assuming a decreasing demand of resources. Vertical elasticity for processing resources could be observed in the workload trace of Table XVIII from $t = 3$ to $t = 4$, where $V_{cpu}''_{111}$ and $V_{cpu}''_{121}$ decrease from $8$ [ECU] to $4$ [ECU], assuming a decreasing demand of resources. Vertical elasticity could also be applied to other resources as described in Section I-C.

For the environment 16, server and network resources utilization change dynamically in all VMs from $t = 0$ to $t = 4$, representing important data for CSPs in order to apply a safe overbooking of both server and network resources.
Figure 1. Basic example of dynamic environment 1 for 5 instants of time (t)

Figure 2. Basic example of dynamic environment 2 for 5 instants of time (t)

Figure 3. Basic example of dynamic environment 3 for 5 instants of time (t)

Figure 4. Basic example of dynamic environment 4 for 5 instants of time (t)
Figure 5. Basic example of dynamic environment 5 for 5 instants of time (t)

Figure 6. Basic example of dynamic environment 6 for 5 instants of time (t)

Figure 7. Basic example of dynamic environment 7 for 5 instants of time (t)
Figure 8. Basic example of dynamic environment 8 for 5 instants of time ($t$)

Figure 9. Basic example of dynamic environment 9 for 5 instants of time ($t$)

Figure 10. Basic example of dynamic environment 10 for 5 instants of time ($t$)
Figure 11. Basic example of dynamic environment 11 for 5 instants of time (t)

Figure 12. Basic example of dynamic environment 12 for 5 instants of time (t)

Figure 13. Basic example of dynamic environment 13 for 5 instants of time (t)
Figure 14. Basic example of dynamic environment 14 for 5 instants of time (t)

Figure 15. Basic example of dynamic environment 15 for 5 instants of time (t)
Figure 16. Basic example of dynamic environment 16 for 5 instants of time (t)
### Table III
**Example of workload trace for VMP problem in Environment 1**

| $t$ | $S_b$ | $D_c$ | $V_j$ | $Vcpu_{t=0}^{v_j}$ | $Vram_{t=0}^{v_j}$ | $Vnet_{t=0}^{v_j}$ | $R_{t=0}^{v_j}$ | $SLA_{t=0}^{v_j}$ | $Ucpu_{t=0}^{v_j}$ | $Uram_{t=0}^{v_j}$ | $Unet_{t=0}^{v_j}$ |
|-----|-------|-------|------|------------------|------------------|------------------|--------------|-------------|----------------|----------------|-------------|
| 0   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 4              | 14             | 150          |
| 0   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 50           |
| 1   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 5              | 14             | 150          |
| 1   | 1     | 2     | 1    | 8                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 50           |
| 2   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 50           |
| 3   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 50           |
| 4   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 50           |

### Table IV
**Example of workload trace for VMP problem in Environment 2**

| $t$ | $S_b$ | $D_c$ | $V_j$ | $Vcpu_{t=0}^{v_j}$ | $Vram_{t=0}^{v_j}$ | $Vnet_{t=0}^{v_j}$ | $R_{t=0}^{v_j}$ | $SLA_{t=0}^{v_j}$ | $Ucpu_{t=0}^{v_j}$ | $Uram_{t=0}^{v_j}$ | $Unet_{t=0}^{v_j}$ |
|-----|-------|-------|------|------------------|------------------|------------------|--------------|-------------|----------------|----------------|-------------|
| 0   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 4              | 14             | 150          |
| 0   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 50           |
| 1   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 5              | 15             | 150          |
| 1   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 4              | 7              | 50           |
| 2   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 6              | 16             | 150          |
| 2   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 5              | 7              | 50           |
| 3   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 5              | 13             | 150          |
| 3   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 5              | 8              | 50           |
| 4   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 5              | 12             | 150          |
| 4   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 50           |

### Table V
**Example of workload trace for VMP problem in Environment 3**

| $t$ | $S_b$ | $D_c$ | $V_j$ | $Vcpu_{t=0}^{v_j}$ | $Vram_{t=0}^{v_j}$ | $Vnet_{t=0}^{v_j}$ | $R_{t=0}^{v_j}$ | $SLA_{t=0}^{v_j}$ | $Ucpu_{t=0}^{v_j}$ | $Uram_{t=0}^{v_j}$ | $Unet_{t=0}^{v_j}$ |
|-----|-------|-------|------|------------------|------------------|------------------|--------------|-------------|----------------|----------------|-------------|
| 0   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 4              | 14             | 150          |
| 0   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 50           |
| 1   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 4              | 14             | 160          |
| 1   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 100          |
| 2   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 4              | 13             | 160          |
| 2   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 90           |
| 3   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 4              | 14             | 150          |
| 3   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 100          |
| 4   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 4              | 14             | 170          |
| 4   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 170          |

### Table VI
**Example of workload trace for VMP problem in Environment 4**

| $t$ | $S_b$ | $D_c$ | $V_j$ | $Vcpu_{t=0}^{v_j}$ | $Vram_{t=0}^{v_j}$ | $Vnet_{t=0}^{v_j}$ | $R_{t=0}^{v_j}$ | $SLA_{t=0}^{v_j}$ | $Ucpu_{t=0}^{v_j}$ | $Uram_{t=0}^{v_j}$ | $Unet_{t=0}^{v_j}$ |
|-----|-------|-------|------|------------------|------------------|------------------|--------------|-------------|----------------|----------------|-------------|
| 0   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 4              | 14             | 150          |
| 0   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 50           |
| 1   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 5              | 15             | 160          |
| 1   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 4              | 7              | 100          |
| 2   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 6              | 16             | 160          |
| 2   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 5              | 7              | 90           |
| 3   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 5              | 13             | 150          |
| 3   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 5              | 8              | 100          |
| 4   | 1     | 1     | 1    | 8                | 16               | 1000             | 0.5          | 1           | 5              | 12             | 170          |
| 4   | 1     | 2     | 1    | 5                | 12               | 1000             | 0.5          | 1           | 2              | 9              | 60           |
### Table VII
**Example of workload trace for VMP problem in Environment 5**

| $t$ | $S_b$ | $D_e$ | $V_j$ | $V_{cpu_{bcj}}$ | $V_{ram_{bcj}}$ | $V_{net_{bcj}}$ | $R_{bcj}^t$ | $SLA_{bcj}$ | $Ucpu_{bcj}$ | $Uram_{bcj}$ | $Unet_{bcj}$ |
|-----|-------|-------|-------|----------------|----------------|----------------|-------------|-------------|-------------|-------------|-------------|
| 0   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 150         |
| 0   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 50          |
| 1   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 150         |
| 1   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 50          |
| 2   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 150         |
| 2   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 50          |
| 3   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 150         |
| 3   | 1     | 2     | 1     | 5             | 16             | 1000           | 0.5         | 1           | 2           | 9           | 50          |
| 3   | 1     | 2     | 2     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 50          |
| 4   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 150         |
| 4   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 50          |

### Table VIII
**Example of workload trace for VMP problem in Environment 6**

| $t$ | $S_b$ | $D_e$ | $V_j$ | $V_{cpu_{bcj}}$ | $V_{ram_{bcj}}$ | $V_{net_{bcj}}$ | $R_{bcj}^t$ | $SLA_{bcj}$ | $Ucpu_{bcj}$ | $Uram_{bcj}$ | $Unet_{bcj}$ |
|-----|-------|-------|-------|----------------|----------------|----------------|-------------|-------------|-------------|-------------|-------------|
| 0   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 150         |
| 0   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 50          |
| 1   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 5           | 20          | 150         |
| 1   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 4           | 10          | 50          |
| 1   | 1     | 1     | 2     | 5             | 12             | 1000           | 0.5         | 1           | 1           | 7           | 50          |
| 2   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 5           | 19          | 150         |
| 2   | 1     | 2     | 1     | 5             | 16             | 1000           | 0.5         | 1           | 5           | 11          | 50          |
| 2   | 1     | 2     | 2     | 5             | 12             | 1000           | 0.5         | 1           | 3           | 9           | 50          |
| 3   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 17          | 150         |
| 3   | 1     | 2     | 1     | 5             | 16             | 1000           | 0.5         | 1           | 7           | 12          | 50          |
| 3   | 1     | 2     | 2     | 5             | 12             | 1000           | 0.5         | 1           | 4           | 9           | 50          |
| 4   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 6           | 20          | 150         |
| 4   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 4           | 11          | 50          |

### Table IX
**Example of workload trace for VMP problem in Environment 7**

| $t$ | $S_b$ | $D_e$ | $V_j$ | $V_{cpu_{bcj}}$ | $V_{ram_{bcj}}$ | $V_{net_{bcj}}$ | $R_{bcj}^t$ | $SLA_{bcj}$ | $Ucpu_{bcj}$ | $Uram_{bcj}$ | $Unet_{bcj}$ |
|-----|-------|-------|-------|----------------|----------------|----------------|-------------|-------------|-------------|-------------|-------------|
| 0   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 150         |
| 0   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 50          |
| 1   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 160         |
| 1   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 100         |
| 1   | 1     | 1     | 2     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 70          |
| 2   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 200         |
| 2   | 1     | 2     | 1     | 5             | 16             | 1000           | 0.5         | 1           | 2           | 9           | 150         |
| 2   | 1     | 1     | 2     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 50          |
| 2   | 1     | 2     | 2     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 60          |
| 3   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 180         |
| 3   | 1     | 1     | 2     | 5             | 16             | 1000           | 0.5         | 1           | 2           | 9           | 120         |
| 3   | 1     | 2     | 2     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 60          |
| 4   | 1     | 1     | 1     | 8             | 16             | 1000           | 0.5         | 1           | 4           | 14          | 200         |
| 4   | 1     | 2     | 1     | 5             | 12             | 1000           | 0.5         | 1           | 2           | 9           | 100         |
### Table X
Example of workload trace for VMP problem in Environment 8

| $t$ | $S_b$ | $D_c$ | $V_j$ | $Vcpu_{bcj}$ | $Vram_{bcj}$ | $Vnet_{bcj}$ | $Rcpu_{bcj}$ | $SLA_{bcj}$ | $Ucpu_{bcj}$ | $Uram_{bcj}$ | $Unet_{bcj}$ |
|-----|-------|-------|-------|--------------|--------------|-------------|-------------|------------|-------------|-------------|------------|
| 0 1 | 1     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 4          | 14          | 150         |
| 1 1 | 2     | 1     | 5     | 12           | 1000         | 0.5         | 1           | 2          | 9           | 50          |
| 2 1 | 1     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 5          | 20          | 160         |
| 3 1 | 1     | 2     | 1     | 5            | 1000         | 0.5         | 1           | 4          | 10          | 100         |
| 4 1 | 1     | 2     | 5     | 12           | 1000         | 0.5         | 1           | 3          | 9           | 50          |

### Table XI
Example of workload trace for VMP problem in Environment 9

| $t$ | $S_b$ | $D_c$ | $V_j$ | $Vcpu_{bcj}$ | $Vram_{bcj}$ | $Vnet_{bcj}$ | $Rcpu_{bcj}$ | $SLA_{bcj}$ | $Ucpu_{bcj}$ | $Uram_{bcj}$ | $Unet_{bcj}$ |
|-----|-------|-------|-------|--------------|--------------|-------------|-------------|------------|-------------|-------------|------------|
| 0 1 | 1     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 4          | 14          | 150         |
| 1 1 | 2     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 2          | 9           | 50          |
| 2 1 | 1     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 4          | 14          | 150         |
| 3 1 | 2     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 2          | 9           | 50          |
| 4 1 | 1     | 1     | 4     | 15           | 1000         | 0.5         | 1           | 6          | 20          | 200         |
| 4 1 | 2     | 1     | 5     | 12           | 1000         | 0.5         | 1           | 4          | 11          | 100         |

### Table XII
Example of workload trace for VMP problem in Environment 10

| $t$ | $S_b$ | $D_c$ | $V_j$ | $Vcpu_{bcj}$ | $Vram_{bcj}$ | $Vnet_{bcj}$ | $Rcpu_{bcj}$ | $SLA_{bcj}$ | $Ucpu_{bcj}$ | $Uram_{bcj}$ | $Unet_{bcj}$ |
|-----|-------|-------|-------|--------------|--------------|-------------|-------------|------------|-------------|-------------|------------|
| 0 1 | 1     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 4          | 14          | 150         |
| 1 1 | 2     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 2          | 9           | 50          |
| 2 1 | 1     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 4          | 14          | 150         |
| 3 1 | 2     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 2          | 9           | 50          |
| 4 1 | 1     | 1     | 6     | 15           | 1000         | 0.5         | 1           | 5          | 12          | 150         |
| 4 1 | 2     | 1     | 6     | 15           | 1000         | 0.5         | 1           | 2          | 9           | 50          |

### Table XIII
Example of workload trace for VMP problem in Environment 11

| $t$ | $S_b$ | $D_c$ | $V_j$ | $Vcpu_{bcj}$ | $Vram_{bcj}$ | $Vnet_{bcj}$ | $Rcpu_{bcj}$ | $SLA_{bcj}$ | $Ucpu_{bcj}$ | $Uram_{bcj}$ | $Unet_{bcj}$ |
|-----|-------|-------|-------|--------------|--------------|-------------|-------------|------------|-------------|-------------|------------|
| 0 1 | 1     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 4          | 14          | 150         |
| 1 1 | 2     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 2          | 9           | 50          |
| 2 1 | 1     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 4          | 14          | 160         |
| 3 1 | 2     | 1     | 8     | 16           | 1000         | 0.5         | 1           | 2          | 9           | 100         |
| 4 1 | 1     | 1     | 4     | 15           | 1000         | 0.5         | 1           | 4          | 14          | 150         |
| 4 1 | 1     | 1     | 2     | 15           | 1000         | 0.5         | 1           | 2          | 9           | 60          |
Table XIV
EXAMPLE OF WORKLOAD TRACE FOR VMP PROBLEM IN ENVIRONMENT 12

| t | S_b | D_c | V_j | Vcpu^l_{t, V_j} | Vram^l_{t, V_j} | Vnet^l_{t, V_j} | R^l_{t, V_j} | SLA^l_{t, V_j} | Ucpu^l_{t, V_j} | Uram^l_{t, V_j} | Unet^l_{t, V_j} |
|---|-----|-----|-----|-----------------|-----------------|-----------------|-------------|-------------|----------------|----------------|---------------|
| 0 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 4              | 14             | 150           |
| 0 | 1   | 1   | 2   | 1              | 8              | 16              | 1000        | 0.5         | 1           | 2              | 9             | 50            |
| 1 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 5              | 15             | 160           |
| 1 | 1   | 2   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 7              | 100           |               |
| 2 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 6              | 16             | 160           |
| 2 | 1   | 2   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 5              | 7             | 90            |
| 3 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 5              | 13             | 150           |
| 3 | 1   | 2   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 5              | 8             | 100           |
| 4 | 1   | 1   | 1   | 4              | 15              | 1000            | 0.5         | 1           | 5              | 12             | 170           |
| 4 | 1   | 2   | 1   | 4              | 15              | 1000            | 0.5         | 1           | 2              | 9             | 60            |

Table XV
EXAMPLE OF WORKLOAD TRACE FOR VMP PROBLEM IN ENVIRONMENT 13

| t | S_b | D_c | V_j | Vcpu^l_{t, V_j} | Vram^l_{t, V_j} | Vnet^l_{t, V_j} | R^l_{t, V_j} | SLA^l_{t, V_j} | Ucpu^l_{t, V_j} | Uram^l_{t, V_j} | Unet^l_{t, V_j} |
|---|-----|-----|-----|-----------------|-----------------|-----------------|-------------|-------------|----------------|----------------|---------------|
| 0 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 4              | 14             | 150           |
| 0 | 1   | 1   | 2   | 1              | 8              | 16              | 1000        | 0.5         | 1           | 2              | 9             | 50            |
| 1 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 4              | 14             | 150           |
| 1 | 1   | 2   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 2              | 9             | 50            |
| 1 | 1   | 1   | 2   | 8              | 16              | 1000            | 0.5         | 1           | 2              | 9             | 50            |
| 2 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 4              | 14             | 150           |
| 2 | 1   | 2   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 2              | 9             | 50            |
| 3 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 2              | 9             | 50            |
| 3 | 1   | 2   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 2              | 9             | 50            |
| 4 | 1   | 1   | 1   | 4              | 12              | 1000            | 0.5         | 1           | 4              | 14             | 150           |
| 4 | 1   | 2   | 1   | 4              | 12              | 1000            | 0.5         | 1           | 2              | 9             | 50            |

Table XVI
EXAMPLE OF WORKLOAD TRACE FOR VMP PROBLEM IN ENVIRONMENT 14

| t | S_b | D_c | V_j | Vcpu^l_{t, V_j} | Vram^l_{t, V_j} | Vnet^l_{t, V_j} | R^l_{t, V_j} | SLA^l_{t, V_j} | Ucpu^l_{t, V_j} | Uram^l_{t, V_j} | Unet^l_{t, V_j} |
|---|-----|-----|-----|-----------------|-----------------|-----------------|-------------|-------------|----------------|----------------|---------------|
| 0 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 4              | 14             | 150           |
| 0 | 1   | 1   | 2   | 1              | 8              | 16              | 1000        | 0.5         | 1           | 2              | 9             | 50            |
| 1 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 4              | 14             | 150           |
| 1 | 1   | 2   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 2              | 9             | 50            |
| 1 | 1   | 1   | 2   | 8              | 16              | 1000            | 0.5         | 1           | 1              | 7             | 100           |
| 2 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 5              | 19             | 150           |
| 2 | 1   | 2   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 5              | 11             | 100           |
| 2 | 1   | 1   | 2   | 8              | 16              | 1000            | 0.5         | 1           | 3              | 9             | 100           |
| 2 | 1   | 2   | 2   | 8              | 16              | 1000            | 0.5         | 1           | 3              | 12             | 100           |
| 3 | 1   | 1   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 4              | 17             | 150           |
| 3 | 1   | 2   | 1   | 8              | 16              | 1000            | 0.5         | 1           | 7              | 12             | 100           |
| 3 | 1   | 1   | 2   | 8              | 16              | 1000            | 0.5         | 1           | 4              | 9             | 100           |
| 3 | 1   | 2   | 2   | 8              | 16              | 1000            | 0.5         | 1           | 5              | 10             | 100           |
| 4 | 1   | 1   | 1   | 4              | 15              | 1000            | 0.5         | 1           | 6              | 20             | 150           |
| 4 | 1   | 2   | 1   | 4              | 15              | 1000            | 0.5         | 1           | 4              | 11             | 100           |
Table XVII
EXAMPLE OF WORKLOAD TRACE FOR VMP PROBLEM IN ENVIRONMENT 15

| $t$ | $S_b$ | $D_j$ | $V_{cpu}$ | $V_{ram}$ | $V_{net}$ | $R^c_{bcj}$ | $SLA^c_{bcj}$ | $U_{cpu}$ | $U_{ram}$ | $U_{net}$ |
|-----|-------|-------|--------|--------|--------|---------|---------|--------|--------|--------|
| 0   | 1     | 1     | 1      | 8      | 16     | 1000    | 0.5     | 4      | 14     | 150    |
| 0   | 1     | 2     | 1      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 50     |
| 1   | 1     | 1     | 1      | 8      | 16     | 1000    | 0.5     | 4      | 14     | 160    |
| 1   | 1     | 2     | 1      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 100    |
| 1   | 1     | 1     | 2      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 70     |
| 2   | 1     | 1     | 1      | 8      | 16     | 1000    | 0.5     | 4      | 14     | 200    |
| 2   | 1     | 2     | 1      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 150    |
| 2   | 1     | 1     | 2      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 50     |
| 2   | 1     | 2     | 2      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 60     |
| 3   | 1     | 1     | 1      | 8      | 16     | 1000    | 0.5     | 4      | 14     | 180    |
| 3   | 1     | 2     | 1      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 150    |
| 3   | 1     | 1     | 2      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 60     |
| 3   | 1     | 2     | 2      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 60     |
| 4   | 1     | 1     | 1      | 4      | 15     | 1000    | 0.5     | 4      | 14     | 200    |
| 4   | 1     | 2     | 1      | 4      | 15     | 1000    | 0.5     | 2      | 9      | 100    |

Table XVIII
EXAMPLE OF WORKLOAD TRACE FOR VMP PROBLEM IN ENVIRONMENT 16

| $t$ | $S_b$ | $D_j$ | $V_{cpu}$ | $V_{ram}$ | $V_{net}$ | $R^c_{bcj}$ | $SLA^c_{bcj}$ | $U_{cpu}$ | $U_{ram}$ | $U_{net}$ |
|-----|-------|-------|--------|--------|--------|---------|---------|--------|--------|--------|
| 0   | 1     | 1     | 1      | 8      | 16     | 1000    | 0.5     | 4      | 14     | 150    |
| 0   | 1     | 2     | 1      | 8      | 16     | 1000    | 0.5     | 2      | 9      | 50     |
| 1   | 1     | 1     | 1      | 8      | 16     | 1000    | 0.5     | 5      | 20     | 160    |
| 1   | 1     | 2     | 1      | 8      | 16     | 1000    | 0.5     | 4      | 10     | 100    |
| 1   | 1     | 1     | 2      | 8      | 16     | 1000    | 0.5     | 1      | 7      | 70     |
| 2   | 1     | 1     | 1      | 8      | 16     | 1000    | 0.5     | 5      | 19     | 200    |
| 2   | 1     | 2     | 1      | 8      | 16     | 1000    | 0.5     | 5      | 11     | 150    |
| 2   | 1     | 1     | 2      | 8      | 16     | 1000    | 0.5     | 3      | 9      | 50     |
| 2   | 1     | 2     | 2      | 8      | 16     | 1000    | 0.5     | 3      | 12     | 60     |
| 3   | 1     | 1     | 1      | 8      | 16     | 1000    | 0.5     | 4      | 17     | 180    |
| 3   | 1     | 2     | 1      | 8      | 16     | 1000    | 0.5     | 7      | 12     | 150    |
| 3   | 1     | 1     | 2      | 8      | 16     | 1000    | 0.5     | 4      | 9      | 60     |
| 3   | 1     | 2     | 2      | 4      | 13     | 1000    | 0.5     | 5      | 10     | 60     |
| 4   | 1     | 1     | 1      | 4      | 13     | 1000    | 0.5     | 6      | 20     | 200    |
| 4   | 1     | 2     | 1      | 4      | 11     | 1000    | 0.5     | 4      | 11     | 100    |
REFERENCES

[1] F. López-Pires and B. Barán, “Virtual machine placement literature review,” CoRR, vol. abs/1506.01509, 2015.