

Evaluating Auto-scaling Strategies for Cloud Computing Environments

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Abstract—Auto-scaling is a key feature in clouds responsible for adjusting the number of available resources to meet service demand. Resource pool modifications are necessary to keep performance indicators, such as utilisation level, between user-defined lower and upper bounds. Auto-scaling strategies that are not properly configured according to user workload characteristics may lead to unacceptable QoS and large resource waste. As a consequence, there is a need for a deeper understanding of auto-scaling strategies and how they should be configured to minimise these problems. In this work, we evaluate various auto-scaling strategies using log traces from a production Google data centre cluster comprising millions of jobs. Using utilisation level as performance indicator, our results show that proper management of auto-scaling parameters reduces the difference between the target utilisation interval and the actual values—we define such difference as Auto-scaling Demand Index. We also present a set of lessons from this study to help cloud providers build recommender systems for auto-scaling operations.

I. INTRODUCTION

Cloud infrastructure is typically elastic, *i.e.* the number of allocated resources can be modified dynamically according to users' needs. Typically, users define an upper bound U and a lower bound L on a target performance metric (*e.g.*, utilisation level, throughput, average response time) to trigger the activation and deactivation, respectively, of a certain number s of resources (step size). Unfortunately, users typically set U , L , and s in an ad-hoc manner, and, as a consequence, performance indicators of cloud solutions are frequently out of their target intervals. In the case of utilisation level, these deviations lead to unsatisfactory QoS and/or use of resources, so they are clearly undesired and should be minimised.

In addition to the challenges involved in the choice of parameters U , L , and s , one must also be careful when selecting an auto-scaling triggering strategy. Several mechanisms addressing this issue rely on forecasts of future resource usage in order to allocate and release resources pro-actively, but there are challenges to these approaches, such as:

- Inherent difficulties in load estimations—especially for environments with heterogeneous workloads;
- The relationship between the monitoring frequency and the time required by the cloud infrastructure to allocate and deallocate resources has a strong impact on the performance of reactive and predictive solutions.

In this article, we discuss and analyse auto-scaling solutions,

which vary according to the chosen strategies for triggering auto-scaling operations and for setting step sizes. We performed computational experiments on real-world data to show the impact of these choices on infrastructure utilisation. In particular, we evaluate the differences between the target interval and the actual measured values and investigate the root causes of undesired deviations. The key contributions of this paper are:

- **Auto-scaling Demand Index (ADI):** a new performance metric for the evaluation of auto-scaling strategies that penalises differences between actual and desired resource utilisation levels (§ II);
- **Adaptive:** a strategy for defining adequate step sizes s in auto-scaling operations based on L , U , and the current system utilisation level (§ III);
- An extensive performance study that compares several auto-scaling strategies based on the **ADI** metric. The study utilises trace logs from a production data centre cluster from Google comprising millions of jobs and considers workloads with various characteristics (§ IV).

II. PROBLEM DESCRIPTION

Cloud users allocate a pool of computing resources to provide services with a certain *QoS* while respecting *budget* restrictions. There is typically a maximum number m of resources they are willing to allocate, but the current number of active elements is ideally kept to a minimum. One performance indicator that takes these two conflicting objectives into account is *resource utilisation level*, which is the ratio between what is currently in use and what is available from the resource pool. Users typically employ rule-based systems that periodically monitor utilisation and trigger auto-scaling operations whenever it is out of a given target interval. Namely, if utilisation goes above an upper bound U , additional resources are allocated to improve QoS, and if it goes below a lower bound L , the resource pool is shrunk to reduce costs.

The aim of this work is to address the following question: “*how to keep resource utilisation inside a target interval*”. To answer this question, we introduce in this article a metric called **Auto-scaling Demand Index (ADI)**, which is the sum of all distances computed between each utilisation level reported by the system and the target utilisation interval set by

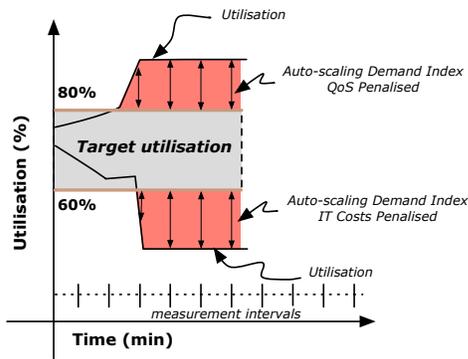
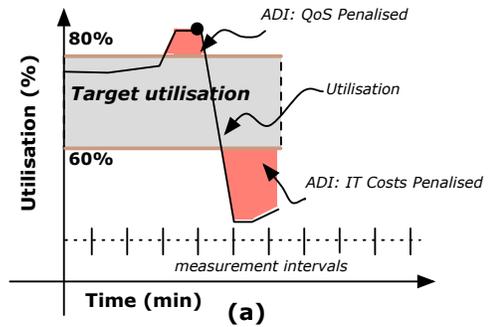


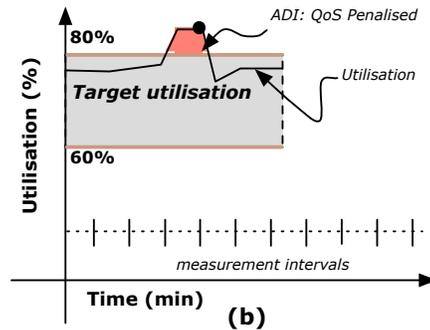
Fig. 1. Auto-scaling Demand Index (ADI) metric. The demand increases either because the actual utilisation is above the upper bound or because the actual utilisation is below the lower bound.

the user. These distances are represented by the thin arrows depicted in Figure 1. ADI is convenient because it employs the same metric to evaluate (or, more precisely, penalise) both unacceptable QoS and resource underutilisation. If the utilisation is above the target interval, QoS is unsatisfactory, since

**Large step size
Auto-scaling Demand Index (ADI) becomes worse**



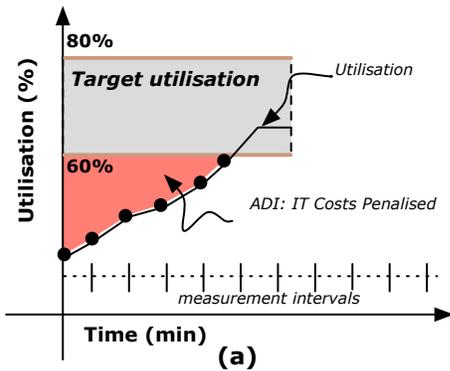
**Small step size
Auto-scaling Demand Index (ADI) reduces to zero**



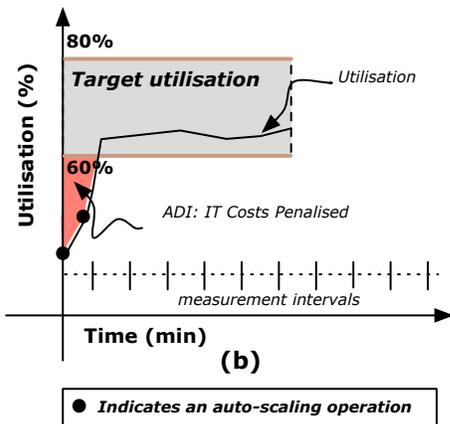
● Indicates an auto-scaling operation

Fig. 3. Problem when utilisation crosses target interval.

**Small step size
Auto-scale is slow to reach the target utilisation**



**Large step size
Auto-scaling is fast reach the target utilisation**



● Indicates an auto-scaling operation

Fig. 2. Problem with slow convergence to the target utilisation interval.

the infrastructure is not enough to meet workload demand. If the utilisation is below the target one, a penalisation incurs due to resource underutilisation.

It is clear that auto-scaling operations are unavoidable if system load is heterogeneous over time, so we are interested in reducing the gap between the actual utilisation and the target interval. Moreover, we remark that the problem is not trivial in situations where workload forecasts are not accurate, since prediction-based strategies will not be able to achieve optimal solutions.

There are two main challenges to execute auto-scaling operations in a way to minimise ADI: the decision on when to trigger auto-scaling operations and on the step size used to expand or shrink the resource pool. The problems related to step size are more subtle, and therefore we highlight some of them in Figures 2 and 3. Figure 2(a) shows a case in which a relatively small step size was adopted and, therefore, several auto-scaling operations were needed for the system utilisation to reach the target interval. If a large step size is used, as shown in Figure 2(b), a single auto-scaling operation may be sufficient, thus reducing ADI drastically. Figure 3(a) shows a scenario in which auto-scaling with a large step size makes the actual utilisation moves from slightly above the target interval

to way below it. If a small step size were used, the utilisation would move to the target interval, as illustrated in Figure 3(b).

The problems described in the above-mentioned scenarios can be minimised if decision-support systems explore analytical relations involving parameters U , L , s , and m in order to have their values adjusted (in particular, the value of s) and to support users that have to set up these values manually. To address these problems, we performed experiments with various workloads and analysed the performance of several auto-scaling strategies according to **ADI**.

III. MODELLING

A. Formal Description

We consider a discrete-time state-space model, so all the time-related values are integer numbers belonging to a set $\mathcal{T} \subseteq \mathbb{N}$. From now on, we refer to each t in \mathcal{T} as a *time-step*.

We are given a set \mathcal{U} of users, a set \mathcal{J} of incoming jobs, and a set \mathcal{M} of machines that can be provisioned and used to service these jobs. The set of jobs being executed at time-step t is denoted by \mathcal{J}_t .

Machines are pairwise indistinguishable, *i.e.*, they all provide the same amount of resources (*e.g.*, number of CPU cores, frequency, memory). For each time-step t , $\mathcal{M} = \mathcal{M}_{a,t} \cup \mathcal{M}_{n,t}$, where $\mathcal{M}_{a,t}$ and $\mathcal{M}_{n,t}$ contain the machines that are currently active and inactive, respectively (it is therefore clear that $\mathcal{M}_{a,t} \cap \mathcal{M}_{n,t} \neq \emptyset$). Finally, $m = |\mathcal{M}|$ and $m_t = |\mathcal{M}_{a,t}|$.

Each job j requires an amount of resources $w_j \in \mathbb{R}^+$. Since w_j is not necessarily integer, jobs may consume only a fraction of the resources that a single machine may provide. Moreover, w_j may be larger than 1, which indicates that job j needs more than one machine to have its requirements satisfied. The amount of resources being used at time-step t is denoted by w_t and is given by

$$w_t = \sum_{j \in \mathcal{J}_t} w_j.$$

In this work, we assume that jobs may take any amount of resources from a machine in order to have their requirements satisfied, *i.e.*, resources can be freely and arbitrarily decomposed. Applications composed of several independent tasks fit well into this scenario. Therefore, jobs in \mathcal{J}_t can be executed if $m_t \geq \lceil w_t \rceil$.

The *utilisation level* of the system at time-step t is denoted by u_t and is given by

$$u_t = \frac{w_t}{m_t}.$$

In every time-step t , users of a cloud service typically want to keep u_t restricted to a certain interval whose lower and upper bounds are denoted by L and U , respectively, with $0 \leq L \leq U \leq 1.0$. Whenever u_t becomes either smaller than L or larger than U , resources (*i.e.*, machines) have to be deactivated

or activated, respectively, if we wish to bring the utilisation level to interval $[L, U]$.

A challenging task associated to auto-scaling operations is defining the step size, which refers to the number s of machines that should be activated or deactivated. Since deviations from $[L, U]$ are undesired, we introduce a metric called **Auto-scaling Demand Index (ADI)** in order to evaluate the quality of auto-scaling strategies. **ADI** is represented by σ and is defined as follows:

$$\sigma = \sum_{t \in \mathcal{T}} \sigma_t,$$

where

$$\sigma_t = \begin{cases} L - u_t & \text{if } u_t \leq L, \\ 0 & \text{if } L < u_t < U, \\ u_t - U & \text{otherwise.} \end{cases}$$

Intuitively, **ADI** is the sum of the distances between u_t and $[L, U]$ for each t , so an optimal auto-scaling strategy according to this metric is the one that delivers minimum σ .

B. Strategies for Triggering Auto-scaling Operations

We consider in this work the following strategies for triggering auto-scaling operations.

Reactive. In the **Reactive** strategy, an auto-scaling operation is triggered at time-step t if $u_t < L$ or if $u_t > U$.

Conservative. In the **Conservative** strategy, an auto-scaling operation is triggered at time-step t if $u_{t-3} < L$, $u_{t-2} < L$, $u_{t-1} < L$, and $u_t < L$ or if $u_{t-3} > U$, $u_{t-2} > U$, $u_{t-1} > U$, and $u_t > U$. That is, the pool of resources will only be changed if deviations in system utilisation of the same nature (*i.e.*, either always above U or always below L) have been observed in the last four time-steps. We chose step windows of size four because preliminary experiments, based on the workloads used in our evaluation, showed that this configuration delivers better results. One could configure the window according to workload characteristics.

Predictive. The **Predictive** strategy is a variation of **Reactive** where decisions about auto-scaling operations are taken not according to u_t , but to u'_{t+1} , an estimate of the system utilisation level on time-step $t+1$ that is computed as follows:

$$u'_{t+1} = \begin{cases} \beta u'_t + (1 - \beta)u_t & \text{if } t > 0, \\ 0 & \text{otherwise,} \end{cases}$$

for $\beta \in [0, 1]$. Preliminary results motivated the choice of $\beta = 0.1$, so we will make no further comments about this parameter in this work.

C. Strategies for Setting Auto-scaling Step Sizes

Once an auto-scaling operation has been triggered, the next decision is the choice of an adequate step size s . We consider the following strategies.

Fixed. In this strategy, step size s is a fixed parameter defined by the auto-scaler user, and its value is employed for all scale-in (shrink) and scale-out (expand) operations.

Adaptive. We introduce a strategy that, in each time-step t , computes a step size s_t according to the current utilisation level u_t . We describe below how s_t should be computed.

If $u_t > U$, the system has to perform a *scale-out operation*, that is, it has to expand m_t by some value s . However, if s is either too small or too large, the utilisation level will potentially stay greater than U . For *scale-in operations*, the situation is analogous. These problems are depicted in Figures 3(a) and 2(a), and their optimal counterparts are presented in Figures 3(b) and 2(b), respectively. Our algorithm tries to avoid these situations by activating a number of machines that would bring the system to a satisfactory utilisation level for w_t .

An upper bound on s during scale-out operations is given by

$$\begin{aligned} \frac{u_t m_t}{m_t + s} &\geq L \\ u_t m_t &\geq L m_t + L s \\ s &\leq m_t \frac{u_t - L}{L}, \end{aligned}$$

while a lower bound on s is given by

$$\begin{aligned} \frac{u_t m_t}{m_t + s} &\leq U \\ u_t m_t &\leq U m_t + U s \\ s &\geq m_t \frac{u_t - U}{U}. \end{aligned}$$

If $u_t < L$, the number s of machines that have to be deactivated is bounded by

$$\begin{aligned} \frac{u_t m_t}{m_t - s} &\geq L \\ u_t m_t &\geq L m_t - L s \\ s &\leq m_t \frac{L - u_t}{L} \end{aligned}$$

and by

$$\begin{aligned} \frac{u_t m_t}{m_t - s} &\leq U \\ u_t m_t &\leq U m_t - U s \\ s &\geq m_t \frac{U - u_t}{U}. \end{aligned}$$

For both situations, let us denote by L_t and by U_t the lower bound and the upper bound derived according to the inequalities above.

Any value in $[L_t, U_t]$ can be selected in auto-scaling operations. Large values for scale-in operations and small values for scale-out operations are suitable for system administrators having an “aggressive” profile, whereas the opposite choices are more “conservative”. In order to incorporate these preferences to the **Adaptive** strategy, we consider an “aggressiveness

TABLE I
SUMMARY OF WORKLOAD INFORMATION.

Workload ID	Max Machines	Tasks
1	2591	8,447,501
2	738	522,696
3	1806	108,962
4	3099	576,246
5	84	158,554
6	3302	6,976,047
7	3224	17,193
8	1048	1,410,776

level” parameter $\alpha \in [0, 1]$. More precisely, given α , for scale-in operations, the value of s_t is

$$s_t = (1 - \alpha)L_t + \alpha U_t,$$

while the value of s_t for scale-out operations is

$$s_t = \alpha L_t + (1 - \alpha)U_t.$$

IV. EVALUATION

The evaluation aims at comparing different auto-scaling strategies using **Auto-scaling Demand Index (ADI)** as metric. We describe relevant details and the process of utilising trace logs from a production data centre cluster from Google, explain the experiments, and present result analysis.

A. Workloads

Google made trace logs publicly available from one of its production data centre clusters, which contains approximately 12K servers and spans a period of one month [1]. The logs contain records of user jobs submitted to the cluster, their CPU consumption, duration, and which machines they used. Each job contains a list of tasks associated with it. These tasks represent the jobs we modelled in Section III. Measurements in the traces have a fixed time interval of 5 minutes.

The traces have 933 distinct and anonymous identifiers, so it is not possible to know if an isolated profile refers to an end-user or to a service. Our evaluation scenario requires actual cloud services that need to expand/reduce their computing capacity. Therefore, to translate sets of identifiers into services, we grouped users with similar CPU consumption behaviour over time using a clustering technique, described below.

For each user u that submitted one or more jobs to the data centre cluster, we extracted a list of triples $(t, w_{t,u}, r_{t,u}) \in \mathcal{T} \times \mathbb{R}^+ \times [0, 1]$, where t denotes the current time-step, $w_{t,u}$ denotes the average amount of resources requested on the previous 5 minutes by jobs of u (see Section III), and $r_{t,u}$ denotes the normalization of $w_{t,u}$ in relation to all the other utilisation measurements for the same user, *i.e.*,

$$r_{t,u} = \frac{w_{t,u}}{\max_{t' \in \mathcal{T}} w_{t',u}}.$$

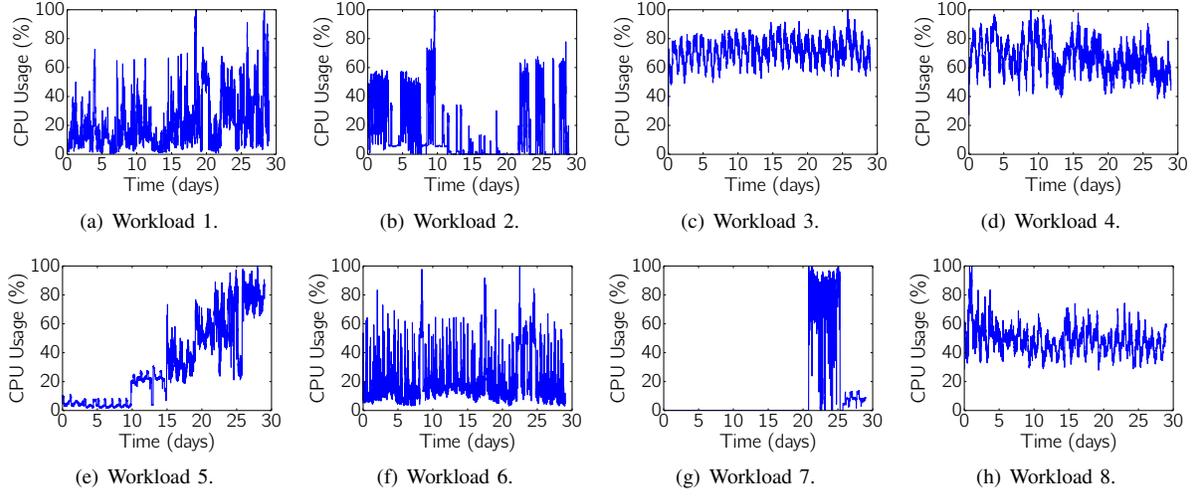


Fig. 4. Workloads after clustering users by their CPU usage pattern into eight groups.

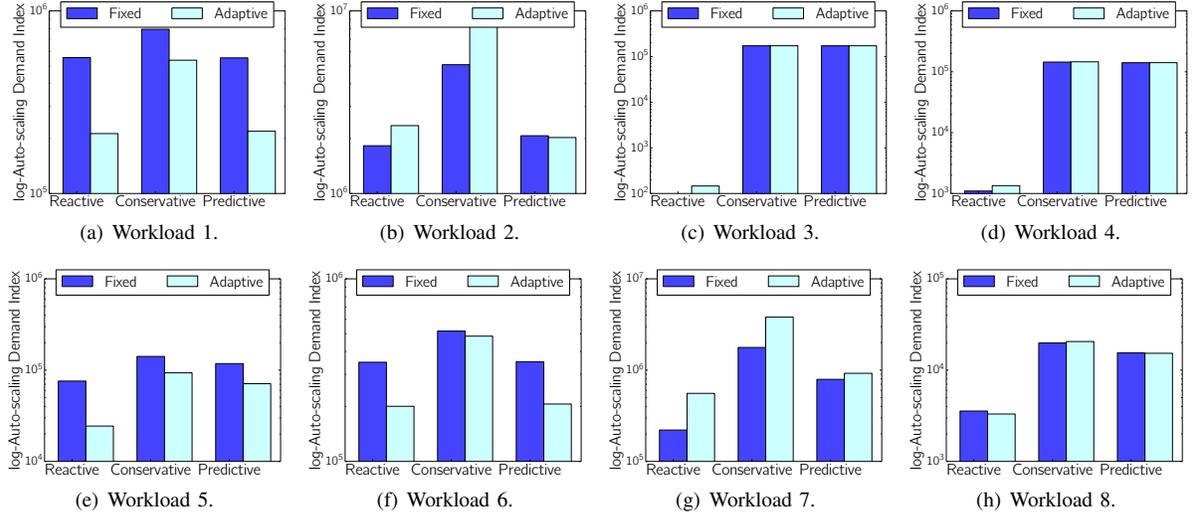


Fig. 5. Summary of Auto-scaling Demand Index (ADI).

In order to organise workloads whose volumes resemble those of medium to large service providers, we partitioned users responsible for submitting jobs from the dataset using k -means clustering. We opted to use eight groups based on visual inspection of the results for values between 5 and 15.

The algorithm receives as input vectors x_1, x_2, \dots, x_n in $\mathbb{R}^{|\mathcal{T}|}$, where $x_i = \{r_{1,u_i}, r_{2,u_i}, \dots, r_{|\mathcal{T}|,u_i}\}$, *i.e.*, the j -th element of vector x_i contains the normalized resource utilisation level of jobs submitted by user u_i at time j . We employed Euclidean distance between vectors as distance metric. Finally, the number of clusters was defined in a way to have a comprehensive set of workloads with different characteristics.

Table I summarises the maximum number of machines able to meet workloads' demand and the total number of tasks for each workload. We observe that the workloads have a fairly heterogeneous values for both number of machines and number of tasks. Figure 4 depicts the eight resulting workloads—each representing a cloud service with different CPU usage patterns. By having these workloads, we were able to perform experiments in various realistic scenarios.

B. Experiment Description

We conducted experiments with the workloads described earlier using several configurations, each consisting of:

- One of the following auto-scaling triggering strategies: **Reactive**, **Conservative**, and **Predictive**;
- One of the following step size configuration strategies: **Adaptive** and **Fixed**
- An upper bound $L \in \mathbb{N}$ for the desired utilisation level, chosen from [39, 59];
- A lower bound $U \in \mathbb{N}$ for the desired utilisation level, chosen from [60, 80];
- Value of step size s to be used by the **Fixed** strategy.

We choose these intervals for L and H because they contain the values that are typically employed in practice. We used $s = \frac{p}{100}m$ for every integer p in $[1, 50]$, which means that the tested step sizes used in the experiments represented some percentage between 1 and 50 of m , the total number of resources available in the cluster. Finally, in every configuration employing the **Adaptive** strategy, we used $\alpha = 0.5$, *i.e.*, $s_t = \frac{L_t + U_t}{2}$. This represents a neutral level of user aggressiveness. The investigation of the impact of this parameter deserves a study by itself, thus it was not considered in this article.

For configurations involving the combination of the **Predictive** and the **Adaptive** strategy, the step size is defined according to the last utilisation level that has been measured, that is, according to u_t . Preliminary tests that used u'_t instead showed poor results, so this type of configuration was not considered in this work.

In the following section, we present and analyse the results of our experiments. We consider only configurations that employ the best step sizes. More precisely, out of the 50 configurations involving **Fixed** (one for each step size), an auto-scaling triggering strategy, and a pair (L, U) , we chose the one delivering minimum **ADI** for fair comparison reasons.

C. Result Analysis

The results of our experiments are summarised in Figure 5. Each pair of bars in each graph is associated to the auto-scaling triggering strategy indicated in the x -axis, and the depicted values are the sum of all **ADIs** for every combination of L and U . Bars on the left and on the right show these sums for configurations using the **Fixed** and the **Adaptive** strategy, respectively. Finally, for better visualisation, we present the values in logarithmic scale.

The comparison between strategies for setting up step sizes shows that there is no clear winner, since each provided the best results in 4 out of the 8 workloads. However, we remark that the advantage of **Fixed** over **Active** in Workloads 3 and 4 is virtually negligible. Conversely, regarding the auto-scaling triggering strategies, our results show that **Reactive** is consistently good, that **Predictive** oscillates, and that **Conservative** is inferior to all of them. The following paragraphs contain detailed explanations of these results and related findings.

Selecting the best step. One of the key challenges associated with the adoption of the **Fixed** strategy is to choose an adequate step size. Since the value does not change over time, users have to find a compromise between selecting values that are good for small changes and values that are better for large oscillations in the system utilisation.

Difficulties on the selection of adequate fixed step sizes are illustrated in Figure 6, which shows the value of step size that minimises **ADI** for each pair (L, U) in three workloads. The graph for Workload 4 is irregular, which is a consequence of its bursty and peaky behaviour (see Figure 4(d)). For Workload 5, we observe three values of best step, a phenomenon that can be explained by the fact that it has three intervals where variations on the utilisation level are very distinct (see Figure 4(e)). Finally, for Workload 6, there is a pattern indicating that the best step size is proportional to the size of the interval $[L, U]$. Large step sizes for small intervals would generate frequent auto-scaling operations for short target utilisation intervals, such as the one depicted in Figure 3(a).

These observations show that, although **Fixed** performs better than **Adaptive** in certain scenarios, the configuration of a system employing this strategy demands a certain knowledge about the characteristics of the workload. This task is specially challenging if the system utilisation suffers from irregular variations, since choosing the most adequate step size for certain periods of time may increase **ADI** in other intervals.

Step Size Strategies. Figures 5(c), 5(d), and 5(h) show that the differences between **Fixed** and **Adaptive** in Workloads 3, 4, and 8 were marginal, and the explanation lays on their relatively “predictable” behaviour. Namely, it is reasonable to expect that, in these cases, step sizes belonging to a certain range will consistently be better than others and that the **Adaptive** strategy will almost always draw values for s_t from this range. Therefore, the step size strategy is not the most important factor in these scenarios.

The **Adaptive** strategy was better for Workloads 1, 5, and 6 (see Figures 5(a), 5(e), and 5(f)) due to their bursty and peaky behaviours (see Figures 4(a), 4(e), and 4(f)). In these scenarios, the utilisation level changes abruptly, so **Fixed** needs a considerably large number of iterations before reaching the desired utilisation level (see Figure 2), whereas **Adaptive** resizes the resources pool immediately in order to reach the desired utilisation level. Conversely, the quick reaction of **Adaptive** has negative consequences if the utilisation level changes abruptly and come back to normal shortly after. The occurrence of such events explains why **Fixed** combined with short step sizes (see the optimal step sizes for Workload 2 in Figure 7) delivers better results for Workloads 2 and 7.

Auto-scaling Triggering Strategies. Figure 5 shows that the **Reactive** strategy had an excellent performance in our tests. This can be explained by the fact that it always reacts immediately to any deviation from the desired utilisation interval. One can also argue that **Reactive** minimises **ADI** because it

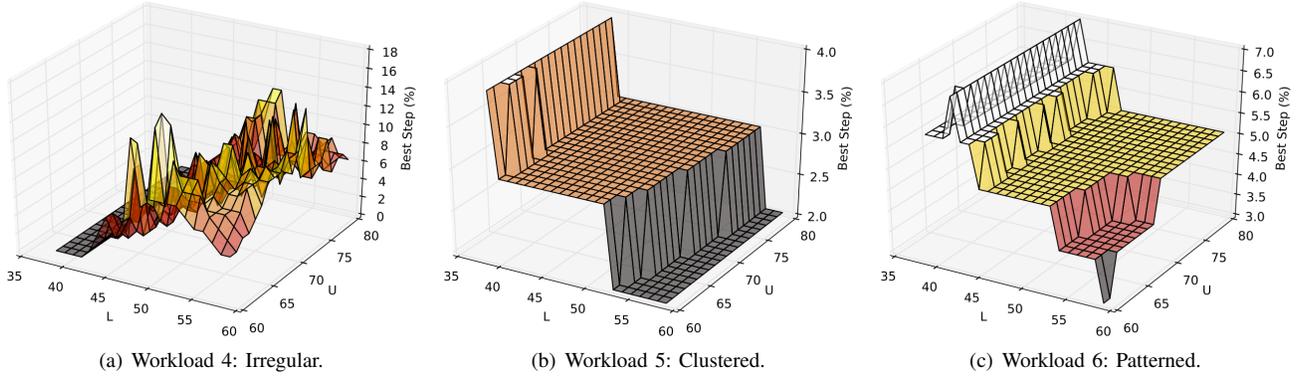


Fig. 6. Different behaviours of best step depending on workload characteristics.

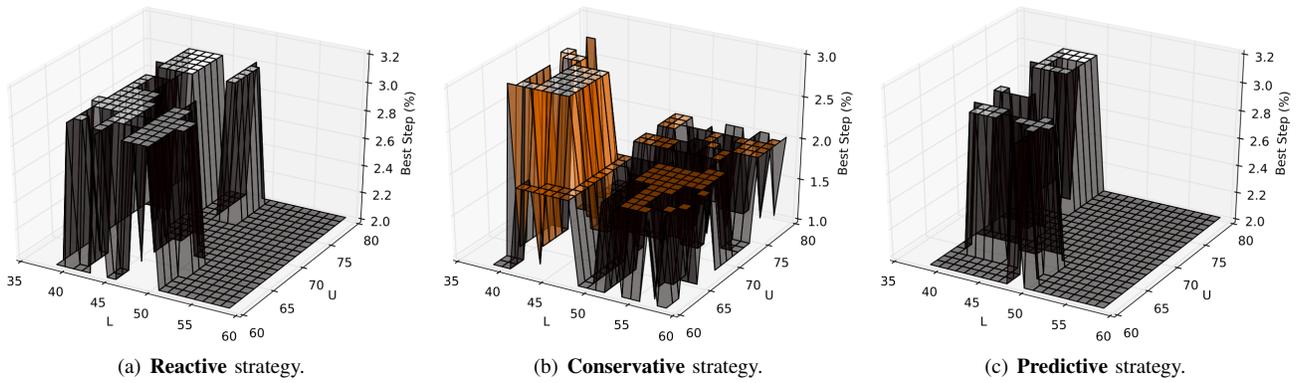


Fig. 7. Optimal step sizes for Workload 2 for different triggering auto-scaling strategies.

does not sacrifice **ADI** in favour of some other metric, such as the number of active resources, QoS, and the number of auto-scaling operations.

The **Conservative** strategy performed poorly in all the workloads, since it waits for the occurrence of four undesired utilisation levels in a row and only starts to react properly after suffering several **ADI** penalties. We remark that the results could have been more favourable to **Conservative** if another metric had been employed, such as the number of auto-scaling operations.

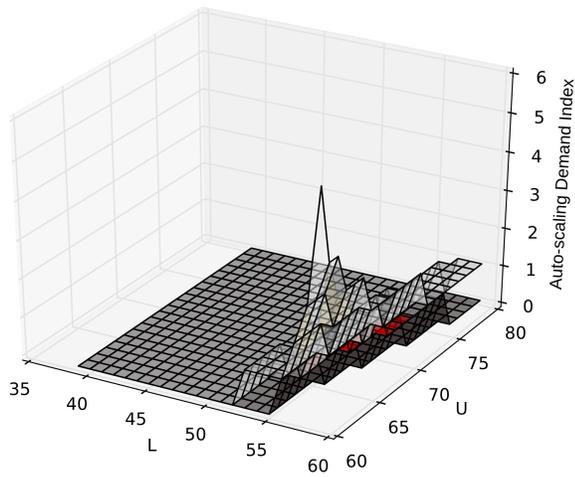
Finally, the **Predictive** strategy was also typically worse than **Reactive**, but the differences were not as large as the ones involving **Conservative**. While the same argument used in the previous paragraph may serve to explain why **Predictive** is superior to **Conservative**, the estimation of u'_t had a significant impact in the results. For Workloads 3, 4, and 8, which were the more “predictable” ones, the exponential smoothing technique delivered poor estimations and lead to several “wrong” auto-scaling operations. For the other workloads, the forecast was better and, in cases were the workload was peaky and

bursty, its results were very similar to those delivered by **Reactive** (e.g., Workloads 1, 2, and 6).

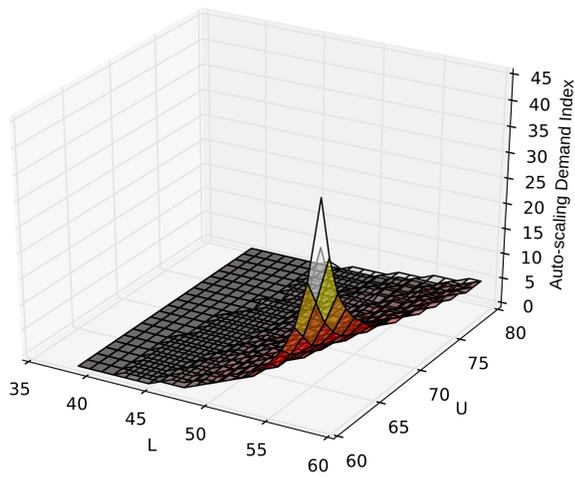
Selection of Utilisation Interval. The performance of the auto-scaling strategies are closely related to the size of the intervals $[L, U]$ in several workloads. It is clear that **ADI** penalties increases as $U - L$ decreases, since the interval where utilisation levels are acceptable is smaller. However, there are some intrinsic aspects from the workloads that deserve careful attention.

In the case of Workload 3, we remark that the system utilisation belonged most of the time to interval $[50, 80]$. Figure 8(a) shows that configurations employing the **Reactive** strategy performed well if $L \leq 50$, while those using $L > 50$ were considerably worse. Workload 4 presents higher variations than Workload 3, so while the same phenomenon can be observed in this case, the changes in **ADI** are smoother (see Figure 8(b)). Finally, the same graph for Workload 5 shows that this decay in performance applies to both step size strategies (see Figure 8(c)).

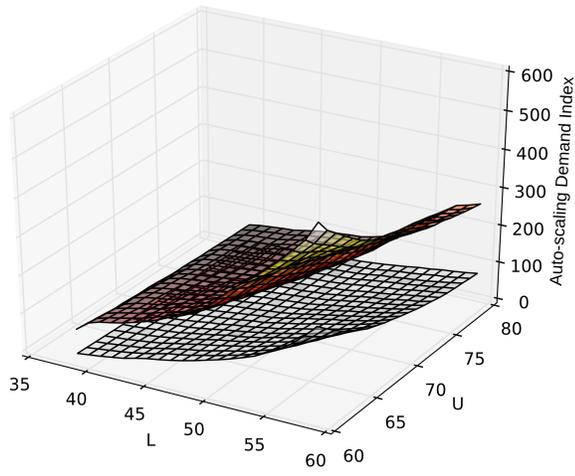
This happens because there is a certain interval to which



(a) **Reactive** strategy.



(b) **Conservative** strategy.



(c) **Predictive** strategy.

Fig. 8. **Auto-scaling Demand Index (ADI)** as a function of target utilisation interval.

most utilisation levels belong to. Once the interval becomes too small, u_t will be very frequently out of $[L, U]$. Differently from Workloads 3 and 4, we see that in Workload 5 the interval would have to be very large, and therefore the performance of both strategies (fixed and adaptive) decays with the size of the target utilisation interval.

V. RELATED WORK

Projects related to our work fall into categories of scheduling and cloud computing auto-scaling.

Scheduling is a well-studied topic in several domains for which the number of theoretical problems, solution approaches, and practical applications is considerably large [2], [3]. Commonly used algorithms include FIFO, priority-based, deadline-driven, hybrid approaches that use backfilling techniques [4], among others [5], [6]. In addition to priorities and deadlines, other factors have been considered, such as fairness [7], energy-consumption [8], and context-awareness [9]. Moreover, utility functions were used to model how the importance of results to users varies over time [10], [11].

Related to our work is Amazon CloudWatch [12], which is a monitoring system to help deciding when Cloud resources need to be modified. In this system, users are responsible for specifying L and U and may not know how to properly setup these values. Microsoft Azure Auto-scaling system [13] also allows users to specify these auto-scaling parameters, but suffers the same limitation from Amazon platform. Scryer [14], from Netflix, is an auto-scaling engine that uses predictive models to know when resources should be added or removed. Its auto-scaling strategy is used internally by the software itself, and thus users do not interact or specify auto-scaling thresholds and policies.

Ming et al. [15] proposed an architecture that deals with auto-scaling focusing on meeting user deadlines. However, it does not consider helping users to define auto-scaling thresholds and resource change steps. Shen *et al.* [16] presented a system to automate elastic resource scaling for cloud computing environments. Their system does not require prior knowledge about the applications running in the cloud. Other projects consider auto-scaling in different scenarios, such as auto-scaling for MapReduce applications [17], [18], vertical versus horizontal auto-scaling [19], operational costs [20], and integer model based auto-scaling [15]. A. Ali-Eldin *et al.* [21] introduced a tool to analyse and classify workloads and assign the most suitable auto-scale controllers based on workload characteristics. Similar to our work, A. Ali-Eldin *et al.* also identified the challenge aspect of developing workload predictors. Recently, we explored the use of user patience information to make better auto-scaling decisions [22].

Our study aims at enhancing existing work on auto-scaling by understanding how to define parameters for this Cloud functionality and how they impact **Auto-scaling Demand Index (ADI)**.

VI. CONCLUSION

In this article we investigated auto-scaling strategies applied to various workload characteristics for cloud computing environments. These strategies involve the definition of when to trigger auto-scaling operations and how to modify the original resource pool depending on the workload variations over time. Our experiments utilised real-world data from a Google cluster, which contains millions of jobs that were grouped to enable the evaluation under different scenarios.

The main contributions of this work are (i) the definition of **Auto-scaling Demand Index (ADI)** to measure the quality of auto-scaling strategies; (ii) an **Adaptive** strategy that configures step sizes according to the current system utilisation level; and (iii) the findings from our experiments involving two step size configuration strategies (**Adaptive** and **Fixed**) and three auto-scaling triggering strategies (**Reactive**, **Conservative**, and **Predictive**).

The main lessons of our evaluation are:

- It is possible to use **Fixed** for auto-scaling when the system utilisation (or any performance metric) is regular and well-known. If workloads are irregular, bursty, and/or peaky, **Adaptive** delivers lower values of **ADI** in comparison to **Fixed**;
- For peaky and bursty workloads, having a fixed step size may require a long time until the resource pool provides the target utilisation interval. This may generate a lost in QoS or a resource waste. The **Adaptive** strategy can then deliver more quickly the target utilisation levels. However, if, for instance, there is a short high peak, the **Adaptive** strategy allocates resources to meet the requirements of that peak, but at the following measurement time, it needs to reduce resources drastically again. In this case, the **Fixed** strategy would not go along at the same level and would deliver a satisfactory performance;
- Predictive strategies may be interesting to help make auto-scaling decisions, but they are very much dependent on workload characteristics and precise prediction models as described by A. Ali-Eldin *et al.* [21]. In situations where the resource provisioning/releasing time is similar or shorter than the measurement intervals, a reactive strategy may adjust the resource pool in a more precise way because it is based on the actual and current workload information. In addition, the effects of the reactive strategy are applied quickly to adapt to the current workload demand;
- Besides the selection of the step size and the triggering moment to execute auto-scaling operations, users still face the challenge of defining the upper and lower bounds for target system utilisation. We observed that depending on workload characteristics, certain intervals may lead

to configurations for which any auto-scaling strategy will have an unsatisfactory performance. Therefore, a recommender system to provide guidance on this aspect becomes fundamental to any cloud provider that wants to enhance user experience.

We believe the findings on the investigated workloads and strategies can help cloud providers build recommender systems for auto-scaling operations.

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