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CLOUD-METRIC: A Cost Effective Application Development Framework for Cloud Infrastructures

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Abstract

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Classic application development model primarily focuses on two key objectives: scalable system architecture and best possible performance. However, This model of application development works well on the private resources, but with the growing amount of public IaaS it is essential to find a balance between the cost and the performance of an application. In this thesis, we have proposed CLOUD-METRIC: A Cost Effective Application Development for Cloud Infrastructures. The framework allows users to estimate the cost of running applications on public cloud infrastructures during the development phase. We will consider two major cloud services providers, Amazon AWS and Google Cloud Platform. The provided estimates can be very useful to make improvements in the users' application architecture. In addition to cost estimation, the framework allows users to monitor resources utilized by their applications. Finally, we will provide users with recommendation of instances on AWS and GCP based on resources utilized by the applications over a period of time.

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Tryckt av: Reprocentralen ITC

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

Alieu Jallow
June 2016

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I am thankful to Google and Amazon for making their cloud pricing data accessible for developers.

Contents

Figures

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Acronyms & Abbreviations

AWS Amazon Web Services

CPU Central Processing Unit

CSV Comma-Separated Values

DRA Durable Reduced Availability

EC2 Elastic Compute Cloud

ECU Elastic Compute Unit

GCE Google Compute Engine

GCEU Google Compute Engine Unit

GCP Google Cloud Platform

GCS Google Cloud Storage

HDD Hard Disk Drive

IaaS Infrastructure as a Service

IOPS Input/Output Operations Per Second

JSON JavaScript Object Notation

PaaS Platform as a Service

PC Pricing Calculator

S3 Simple Storage Service

SaaS Software as a Service

SCVMM System Center Virtual Machine Monitor

SMC Simple Monthly Calculator

SNIC Swedish National Institute of Computing

SSD Solid State Drive

UML Unified Modeling Language

Chapter 1

Introduction

1.1 Problem Description

The promise of Cloud computing is to deliver scalable access to a large pool of computational, storage and network resources, commonly known as Infrastructure-as-a-Service (IaaS). Based on the IaaS it further enables set of high-level services such as Platform-as-a-Service (PaaS) and Software-as-a-Service (SaaS). The model of efficient provisioning of resources is in favor of both services provider and end-users. Users only pay for the usage whereas service provides have well defined economic model together with service level agreements.

Public Clouds offer competitive pricing model and platforms like Amazon Spot[3] market allows users to rent services on even lower cost. The cost model consists of number of parameters such as number of CPUs, Memory and disk size, operating system and network. However the cost of running large-scale applications are still above the borderline. One of the major reasons for this is often applications are designed to attain best performance. This model of application development works well on the private resources but with the growing amount of public IaaS it is essential to find a balance between the cost and the performance of an application.

In this project we developed a framework to estimate the cost of running an application in cloud environment. The aim is to estimate the execution cost during the development phase so that it will be possible to tune the application accordingly. CLOUD-METRIC will be used to maintain a balance between performance and the execution cost of an application. Initially the focus will be on data-intensive processing environments like Hadoop and Spark. The framework will meter the execution and based on the cost matrix it will estimate the overall price of the execution.

Finally, to provide the balance between cost and performance of application, the framework, through an optimization model, will provide recommendation for users on the most cost-efficient instance types on Google Cloud Platform (GCP) and Amazon Web Services (AWS) without compromising performance of application. The model will take parameters from resource monitoring data, pricing model from AWS and GCP, and instance types specifications from AWS and GCP.

1.2 Aims of Project

In this project we proposed a framework for estimating cost of running applications in cloud infrastructures. The primary aim of this project is to provide users (developers) the ability to estimate cost of large-scale applications in public cloud infrastructures specifically, AWS and GCP. The estimated cost are calculated based on on-demand monthly charges from GCP and AWS billings systems.

In addition to providing the estimated monthly cost on GCP and AWS, the proposed framework provides metrics on the resources utilization in the users development environment as well as a recommendation for instances types that minimizes the monthly estimated costs while maintaining or improving application's performance.

1.3 Motivation

Cloud computing has gained significant popularity in the recent years. As a result, many researchers and industrial professionals are considering leveraging cloud computing, which provides the compute power and the resources required to efficiently run applications and store huge amounts of data. Although the cloud computing provides the resources and computing power needed to support large-scale applications and massive data storage, many researchers and professionals have reservations using the cloud for several factors. One of the major factors is cost. In fact Cost, Networking, and Elasticity are the top three dominant factors influencing the adoption of cloud computing for science[4].

Is it a myth that cloud resources is cheap? Our proposed cost-effective framework will demystify this misconception of cloud computing by providing users cost estimates of running applications in two public clouds, AWS and GCP. The framework will meter users' development environment and recommend instances on AWS and GCP that matches their environment. The overall impression of running applications in AWS and GCP will be provided by our proposed framework.

Several researchers including [5] and [6] provide guides to running applications in the cloud. [6] proposed an approach to estimated the cost of running applications on AWS during design phase. [5] proposed a guide for deploying legacy web applications on cloud infrastructures. However, the proposed approaches in [6] and [5] does not provide cost estimates. [6] solution is limited in providing cost estimate that reflect billings in public cloud providers because an application implementation may differ from its initial design. Our framework in this project provides for users the ability to get cost of application while it is being developed. Simultaneously, the user will have the functionality to see which part of their application is consuming more resources so that they could tune the application.

1.4 Scope

In this thesis project, the focus is to provide an estimated cost of running applications in public cloud infrastructures such as Google Cloud Platform and Amazon Web Services. The estimated cost are not exactly same as the cost on the GCP Pricing Calculator and AWS Simple Monthly Calculator. However, the estimated cost is very close to the exact AWS and GCP billing costs.

The estimation of the cost is based on metered computer resources usage parameters such as number of vCPUs, memory size, and disk storage size. Our framework passes the metered parameters to our matching algorithm that maps them to a closely matching instance on AWS and GCP that has the most minimal cost and returns an estimated cost for each of the instances in a month. However, the framework does not consider the low-level differences in hardware resources between our test environment and the Google Cloud and between test environment and AWS. These differences include processor speeds, hardware vendors, and other hardware-specific parameters such as AWS' ECU and GCP's GCEU. The reason we have not considered this details is that the public cloud providers do not use these hardware-specific details to compute the cost of running their instances. Besides, it would be much more complicated to provide cost estimate one instance type with varying hardware-specific details.

In our proposed framework, we implemented a resource monitoring use case that allowed us to provide recommendation for instance types on GCP and AWS that minimizes cost and maintain or improve performance of users' applications. In our framework, the monitoring is limited to only basic parameters used by AWS and GCP for cost estimation and instances type specifications such as number of CPUs, memory usage, and disk usage.

1.5 Structure of Report

The rest of the report is organized as follows: In chapter 2, We discussed related works in detail. We outlined relevant theoretical concepts, public cloud providers and their respective pricing model in chapter 3. In chapter 4 we describe our framework design and implementation. Chapter 5 discusses results of framework evaluations and in Chapter 6 we outlined the conclusion, and future work.

Note: We have used on several occasions instances, nodes, machines, and virtual machines or VMs interchangeably. We mean the same thing. We have also used instance types and machine types interchangeably. This is because Google uses machine types to refer to Compute Engine virtual machines and AWS uses instance types to refer to EC2 virtual machines.

Chapter 2

Related Work

2.1 Overview

As cloud computing provides the needs of researchers and industry professional such as on-demand self-service, rapid elasticity, broad network access, large pool of compute resources, and measured services [7] there has been an increase in its adoption over recent years. On measured services characteristic of cloud computing, several tools have been developed, utilizing various billing models, to provide cloud services providers the ability to bill users on for resources used on monthly basis. The most widely used model is the "Pay-as-you-go", which is adopted by all major cloud services providers. On the other hand, cloud services providers have developed tools such as GCP Pricing Calculator, AWS Simple Monthly Calculator that allow users to estimate cost of adopting services on cloud environments such as EC2, GCE, AWS S3 etc.

However, such estimation are limited as they do not provide the users the ability to relate the estimated cost with application-specific characteristics such as design, implementation, performance, and resources usage. In addition, the actual cost of running an application may be much more higher than what is being estimated using the calculators as the application might consume lots of resources such as network, CPU, and memory, which could be tune and optimized during development. And for large-scale distributed applications, there is need for framework that allow developers to see how much resources are being consumed during development. Such a framework would allow the tuning of the application so that eventually resources utilization and cost are minimized while performance is improved or maintained. This is the problem we are solving in this thesis project.

2.2 Similar Works

Researchers across the community have carried out several research projects relating to metering and cost estimation in cloud environments, from smart metering systems by [8] to monitoring resources by [9], from cost estimation on AWS by [6] to guide to deploying legacy web application in the cloud by [5]. [5] proposed a cloud guide that help users estimate the cost of cloud deployment and performance of legacy web applications. In this paper, Liew at al. used a queuing model to predict the cloud computing resources used by a targeted application and based on that it estimates the deployment cost. The cost is estimated considering the applications' resource costs and services costs. The performance requirements of the application is predicted using defined policies.

A more similar proposed solution to our work is that proposed by Huihong He et al. in [6] in which they proposed an approach to estimating the cost of running application of AWS during design phase. They modeled the application execution service with a UML activity diagram. The UML activity is extracted automatically with a proposed extraction algorithm. In addition, He at al. proposed a cost model to estimate operating cost during design phase and performance need with an algorithm to produce a suitable purchase solution.

[8] proposed pricing of cloud services based on dynamic operational cost of running an instance with the base cost provided by the cloud service providers such as Amazon and Rackspace. The charge of their proposed pricing model is based on leased period like Amazon reserved instances. Resource monitoring tools such as Hyperic was used for monitoring infrastructure resources. [8] also proposed the use of performance counters from hypervisor vendors to obtain cloud instance resource utilization.

Microsoft, being one of the major public cloud services providers, have deployed a tool that help IT managers to quickly assess the running cost of an existing on-premise workload on Azure cloud environment[10]. The tool performs a scan on the existing on-premise workload and recommends a matching instances on Azure. It also provides a monthly cost of the matching instances on the Azure environment. However, the tool is limited to Microsoft and VMware technologies such as Hyper-V, SCVMM, vCenter and ESXi. In our proposed framework, we perform an instance matching routine similar to their matching routine incorporated in this tool but, we match instances to AWS and GCP instances instead.

2.3 Limitation of Related Work

Despite all the works of several researchers in the community and the industry relating to cost estimation in cloud infrastructure, none of them have addressed the problem we have solved in this thesis project: equipping developers with a lightweight framework that allows them to know the cost of running applications in AWS and GCP while in development phase and provide metrics on the resources utilized to not only allow application tuning, but also recommend optimal instances on AWS and GCP. The proposed solution in [6] is liable to provide inaccurate cost estimates as the initial design of the application, with which the cost estimate were made, changes. To get accurate cost estimate would require running the tool each time for each design changes which would be handy.

Chapter 3

Theoretical Concepts

In this chapter, we discussed the relevant theoretical concepts to the proposed framework. Later in the chapter, we outlined the public cloud providers we have considered in the framework and their respective cloud services and pricing models.

3.1 Cloud Computing

Cloud computing, according to [7], is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g. networks, servers, storage, applications and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. A cloud infrastructure is the collection of hardware and software that enables the five essential characteristics of cloud computing. The cloud infrastructure can be viewed as containing both a physical layer and an abstraction layer. The physical layer consists of the hardware resources that are necessary to support the cloud services being provided, and typically includes server, storage and network components. The abstraction layer consists of the software deployed across the physical layer, which manifests the essential cloud characteristics. Conceptually, the abstraction layer sits above the physical layer[7].

3.1.1 Characteristics

Cloud computing has several characteristics: **rapid elasticity** – capability to provision compute resources on demand or release resources so as to scale up or down on customers' demand; **on-demand self-service** – capability that enables user to provision resources and services without intervention of services providers; **Broad network access** – capability to access resources and services over network or standard mechanism like thin or thick clients; **Resources pooling** – means computing resources are pooled to serve multiple customers on a multi-tenant model and resources are dynamically assigned and reassigned without customers knowledge; **Measured Services** – resources and services usage are measured, controlled, and monitored to provide transparency for both provider and consumer of the utilized service.

3.1.2 Deployment Models

Cloud computing has three deployment models namely public cloud, private cloud, community cloud, and hybrid cloud.

- **Public Cloud** – In this model, multiple tenants use a single virtual machine and each pay for the resources they consume. It is provided by a cloud service provider. Examples include Amazon EC2, Microsoft Azure, Google Compute Engine
- **Private Cloud** – In this model, a company manages its own data center that provides scalability, provisioning, automation and management. The company gains the benefits of cloud computing with private cloud, but incur the cost of maintaining it as well.
- **Hybrid** – This model allows a company to maintain an internal private cloud while using public cloud as needed.

3.1.3 Services Models

Cloud computing has three services models[7], which includes Infrastructure-as-a-Service (IaaS), Platform-as-a-Service (PaaS), and Software-as-a-Service (SaaS). Each of service models show a boundary between what the cloud services provider manage and what customers manage. In IaaS, the customers are provided with the underlying infrastructure where they could deploy arbitrary software including operating systems and applications. In PaaS, customers do not manage the underlying cloud infrastructure such as operating systems, servers, network but rather manage applications developed using tools and libraries supported by the providers. In SaaS, the capability provided to the customer is to use providers' applications running on cloud infrastructure such as email services, spreadsheets and word processor applications. Our framework is designed to allow users to estimate cost of application running in the IaaS service model. The figure 3.1 shows the the services models and associated providers.

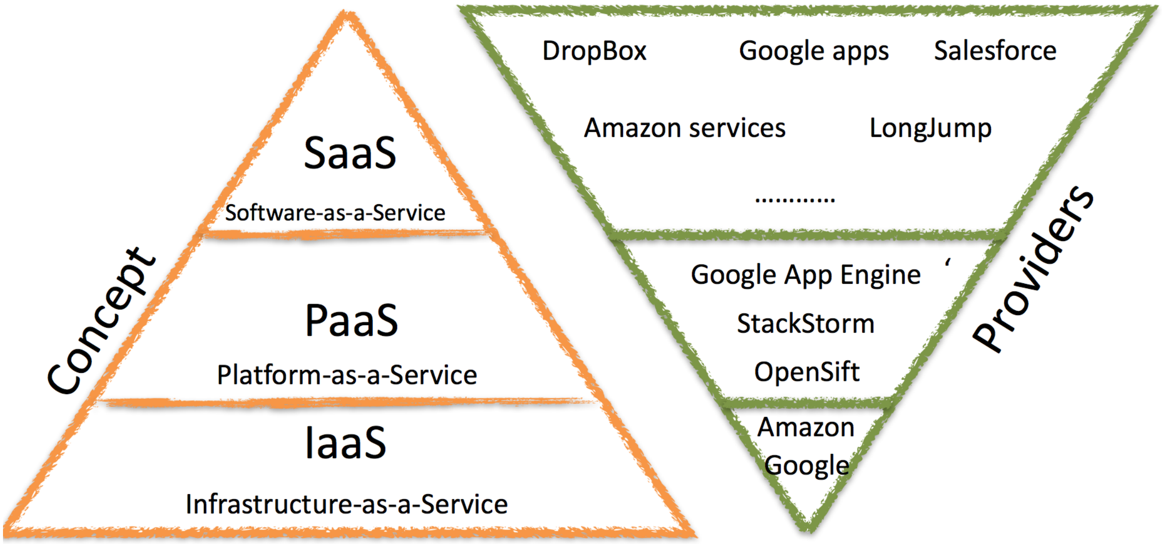


Fig. 3.1 Services models in cloud computing and example of corresponding service providers.

3.2 Public Clouds Providers

In this project, we provide estimated monthly cost from major public clouds providers. The chosen public cloud providers are Google Cloud Platform (GCP) and Amazon Web Services (AWS). Other public cloud providers include Microsoft Azure, and Rackspace.

3.2.1 Amazon Web Services

Amazon Web Services (AWS) is the collection of cloud computing services offered by Amazon[11]. Being the first public cloud services provider, provides a highly reliable, scalable, low-cost infrastructure platform in the cloud that powers hundreds of thousands of businesses in 190 countries around the world[12]. AWS offers services including Amazon EC2, Amazon S3, Amazon DynamoDB, Amazon CloudFront, Amazon EBS, Amazon Beanstalk, etc. In this project, we consider Elastic Compute Cloud (EC2), Elastic Block Store (EBS), and Simple Storage Service (S3).

Amazon EC2

EC2 is a web service that provides resizable compute capacity in the cloud. It provides an interface that allows users to obtain and configure capacity with minimal friction. The EC2 allows customers to take control of their provision compute resources. Within EC2, there are several instance types classified in accordance with hardware resources such as number of virtual CPUs , memory size, and an underlying hardware resource called EC2 Compute Unit ECU. EC2 instances are further grouped into five classes namely Compute Optimized, Memory Optimized, Storage Optimized, GPU Instances, and General Purpose. List of AWS EC2 instance types is outlined in Appendix A, table A.1. EC2 instance have attached EBS volumes, which provide persistent block storage. EBS volumes offer consistent and low-latency performance for workloads. The available EBS volumes types include EBS General Purpose SSD, EBS Provisioned IOPS SSD, Optimized Throughput HDD, Cold HDD, and older generation Magnetic Disks.

Amazon S3

Amazon S3 provides secure, highly-scalable, and safe object storage. Via a web interface customers could store and retrieve large amount of data from any where on the web. S3 provides the data storage needs of customers on AWS.

Amazon EBS

Amazon Elastic Block Store (EBS) provides persistent block-level storage volumes for use with EC2 instances. It provides high availability and durability. It gives customers the capacity to scale up and down with minutes while paying for only what is provisioned. In AWS cloud, EC2 instances also differ with the kind of volume storage available – some flavors provide EBS, others provides SSD storage[1].

3.2.2 Google Cloud Platform

Google Cloud platform is the cloud computing platform that is provided by Google. GCP provides hosting and other cloud services on the same cloud infrastructure that Google uses internally for its products such as Youtube, and Google Search. Over recent years, Google has added several cloud services on top of the App Engine – the PaaS service that was initially launched – to compete with it biggest competitor Amazon AWS, and Microsoft Azure. These services include Compute Engine, Container Engine, Storage, BigQuery, Vision API, etc. In this project, we are delving into its compute infrastructure, and Storage.

GCP Compute Engine

Google's cloud computing IaaS is GCP's Compute Engine. Compute Engine provides provides high-performance and scalable virtual machines (VM) running on Google's innovative data centers connected by a global fiber network[13]. Compute Engine provides users the choices to create custom Machine Types or choose from a set of predefined sizes. A list of the predefined instances is outlined in Appendix A, table A.2.

Disk Storage

Google provide persistent block storage for its Compute Engines. The persistent block storage is available in two types: persistent HDD volume and local SSD volumes.

Google Cloud Storage

Google Cloud Storage is the equivalent of AWS S3 on the GCP. It provides users with durable and highly available object storage[14], which is available in three different options for customers to choose from depending on the needs of their applications – Standard, DRA, and Nearline storage. The storage choices in this framework uses the standard option.

3.3 Cloud Pricing Models

Cloud pricing models varies from provider to provider. For example, the pricing model on Amazon Web Services varies from that of Google Cloud. The most important goals for cloud services providers is profitability and revenue maximization[15], whereas users are more concerned with Quality of Services (QoS), high availability of resources, and cost-effectiveness. To handle this trade-off, cloud services providers have adopted the scheme of dynamic pricing models such as the Amazon Spot instances [3] [15]. The most widely known pricing model is the "Pay-As-You-Go"[15] model, which is adopted by all cloud service providers. Another pricing model is the subscription-based model in which users subscribe to use compute resources for a fixed period of time (usually between 1 to 3 years). As the demand for use of cloud services increases over the years and provision of public cloud services became more competitive among Amazon, Microsoft, and Google, several pricing discounts schemes have been incorporated on top of existing pricing models. This has led to the huge reduction in cloud services costs on all major providers over recent years. In the next few sections, we have outlined the pricing schemes from Amazon AWS and Google Cloud Platform.

3.3.1 Pricing on AWS

Apart from the free usage tier, which allows potential customers to get started on AWS services, AWS charge the rest of its cloud services. For each service, users pay for exactly the amount resources utilized. Amazon pricing models includes:

- **Pay as you go**. In this model, users pay for only what they use. For EC2 instance, user pay for hourly charges from the time of starting an instance until termination. For data storage and transfer, AWS charges per gigabytes basis. Charge depends on the underlying infrastructure and resources consumed. This is also referred to as "On-demand" pricing model. We have used this pricing model in our framework for estimating the cost of running instances.
- **Pay less on Reserve**. Users could get up to 60% discount on reserve instances over equivalent On-Demand capacity. This, however, depends on the instance types used.
- **Pay even less per unit for 100% usage**. For storage and data transfer, pricing is tiered. Users could pay less when they used more. For EC2, user could get up to 10% discount when they reserve more.

AWS has three fundamental characteristics that customers pay for and have the greatest impact on cost[16]. This characteristics include compute, storage, and data transfer out. Our framework considers compute infrastructure and its persistent storage costs.

EC2 Pricing

Cost estimation on Amazon EC2 considers the following:

- Clock Hours of Server Time – the total number hours server runs with a specified period of time, e.g 30 days;
- Machine Configuration – instance pricing varies from regions, OS, number of vCPUs, and memory;
- Machine Purchase Type – Prices varies from On-Demand, Reserve or spot instances;
- Number of Instances – No more instance used the more charges are incurred;
- Operating Systems and Software Packages – Except for some Linux variants such as Ubuntu, Debian,etc, OS are charge with the instance[16].

Pricing formula

Below is a formula for computing the monthly cost of a single AWS EC2 instance:

$$Cost_{monthly} = Cost_{hourly} \times T_{uptime} + Storage_{size} \times Storage_{unitcost}$$

where $Cost_{monthly}$ is instance monthly cost, $Cost_{hourly}$ is hourly unit cost, T_{uptime} is uptime in hours per month, $Storage_{size}$ is the disk size, and $Storage_{unitcost}$ is unit cost of disk type per GB per month. In AWS, EC2 unit cost includes the operating system cost as well.

S3 Pricing

AWS S3 pricing considers storage class, storage size, requests, and data transfer[16]. Storage class includes standard storage and Standard – Infrequent Access storage, and Glacier. The former has a higher percentage of availability than the latter, while the percentage of durability is same – 99.999999999%. The size of storage is charged on a per GB basis. As for requests, GET request gets more charges than others such as

PUT, and POST. Charges are incurred on data transferred out of region on a per GB basis.

EBS Pricing

Amazon EBS provides persistent volumes storage for EC2 instances. EBS volumes are charged by the amount provisioned per GB per month. There are three types of EBS on AWs: General Purpose (SSD), Provisioned IOPS (SSD), and Magnetic[16]. Input Output Operations per Second (IOPS) are charge based on number of requests made to volume on Magnetic. IOPS charge is included in General Purpose SSD cost. In Provisioned IOPS, it is charged based on the number of IOPS provisioned. EBS provides snapshot for backups of instances on S3 for durable recovery. EBS snapshots are charged per GB-month of data stored.

3.3.2 Pricing on GCP

Google Cloud Platform offers pricing of up to 50% less than other cloud providers[17][18]. The GCP offers per minutes billing and automatic discounts on increased usage. Customers pay monthly for on-demand usage of virtual machines instances. In addition, the minimum per minute billing is 10 minutes and usage is rounded up to the nearest minute. Furthermore, Google offers Sustained Usage discounts which means the more customer used, the greater the discount.

Compute Engine Pricing

Google offers two categories of machine types: Predefined machine types and Custom machine types. Predefined machine types have preset virtualized hardware properties and a set price while custom machine types are priced with number of virtual CPUs and memory the instance uses[17]. The Predefined machine types are further grouped into several classes. These include Standard, Shared-core, High Memory, High CPU machine types. This class of predefined machine types are qualified for the Sustained Usage Discount. All machine types on GCP are charged a minimum of 10 minutes and increments after 10 minutes are rounded up to the nearest minute.

On Compute Engine, GCP charges for premium images and the prices differ based on machine types where they are used. The prices for all premium images such as SUSE linux, Red Hat Enterprise Linux, and Window server images are added to the price of the machine type. The premium image prices differ per image and the machine type it is running but the prices are same in all regions[19]. SUSE images are charged $0.02 per hour for f1-micro and g1-micro machine types and $0.11 per hour for all other machine types. RHEL images are charged $0.06 per hour for all machine types with 4 or fewer vCPUs and $0.13 per hour machine types with more than 4 vCPUs. Windows server images are charged $0.02 per hour for f1-micro and g1-micro machine types and $0.04 per core per hour for all other machine types. We have added all this details to our cost estimation routines of the framework.

GCP provides a discount scheme called **Sustained Usage Discount** on all its predefined regular machine types for on-demand subscription. When a predefined machine type runs more than 25% of a month, compute engine give an automatic discount on every minute added. This scheme gives a net discount of up to 30%(See figure 3.2) for an instance that run the entire month[19].

Pricing formula

Below is formula for computing the cost of a single instance on GCP:

$$Cost_{monthly} = Cost_{hourly} \times T_{uptime} \times Discount_{su} + Storage_{size} \times Storage_{unitcost} + OS_{unitcost} \times T_{uptime}$$

where $Cost_{monthly}$ is instance monthly cost, C_h is hourly unit cost, T_{uptime} is uptime in hours per month, $Storage_{size}$ is the disk size, $Storage_{unitcost}$ is unit cost of disk type, $Discount_{su}$ is the Sustained Usage Discount which equals 0.70 for maximum monthly usage, $OS_{unitcost}$ is premium operating system unit cost. In GCP, OS cost are not included in the machine type hourly unit cost. OS is computed separately.

Disk Pricing

Users has the option attach volumes to their machine types on GCP Compute Engine. GCP provides persistent disk, persistent snapshot and local SSD. Persistent disks are charge for the amount of provisioned space per disk and the I/O operations charges are included in the charge for space provisioned. Persistent Snapshot are charged only for the total size of the snapshot and local SSD are charged for the amount of provisioned space per machine at a rate of $0.218 per GB per month. Local SSD are sold at 375 GB increments[19].

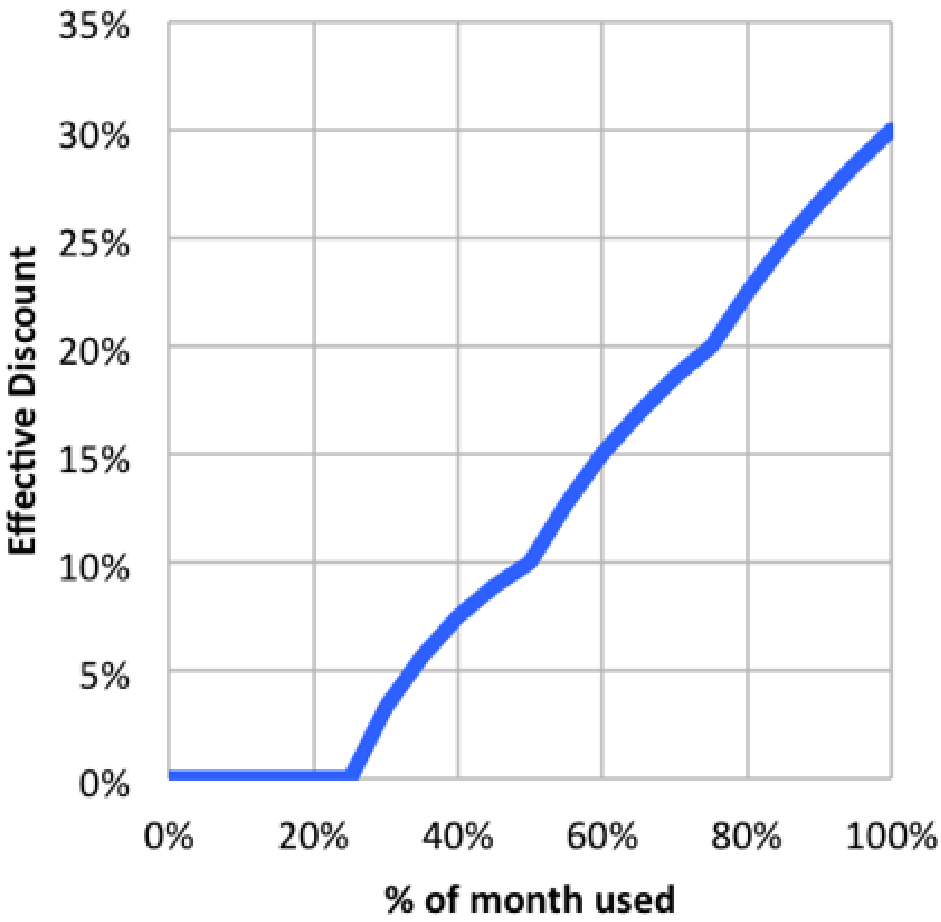


Fig. 3.2 GCP Sustained Usage Discount scheme

Storage Pricing

GCP provides three options for cloud storage, Standard, DRA, and Nearline. The framework uses standard storage cost for storage cost computation. GC storage cost are as follows: Standard storage \$0.026 per GB per month, DRA \$0.02 per GB per month, and Nearline \$0.01 per GB per month[20].

Chapter 4

Design and Implementation

4.1 Overview

The proposed cost-effective framework is designed with portability and robustness in mind. It is developed with Python and Flask micro-framework. The framework used a NoSQL database – MongoDB – to store data relating to instances in users development environment. The framework portability allows it to be deployed either on the same network as the development environment or on an entirely different network. In this chapter, we outlined the pricing data we used to estimate monthly cost, the framework architecture, and the functionality.

4.2 Pricing Data

First in the framework development was the thorough literature survey on the pricing models of GCP and AWS. You will find details of the pricing models in chapter 3.

The pricing data lists of both GCP and AWS was extracted from [21] and [22]. GCP pricing list was readily available for developers in JSON format. However, AWS pricing list was not readily available and had to extracted by Python scripts in CSV formats. Figure 4.1 shows the sample pricing data extracted from AWS.

4.2.1 Pricing Data Validation

Following the extraction of the price list data from AWS and GCP, is the validation of the data in comparison with currently used pricing data on GCP PC and AWS

```
us-east-1,c3.2xlarge,linux,0.42
us-east-1,c3.4xlarge,linux,0.84
us-east-1,c3.8xlarge,linux,1.68
us-east-1,g2.2xlarge,linux,0.65
us-east-1,g2.8xlarge,linux,2.6
us-east-1,r3.large,linux,0.166
us-east-1,r3.xlarge,linux,0.333
us-east-1,r3.2xlarge,linux,0.665
us-east-1,r3.4xlarge,linux,1.33
us-east-1,r3.8xlarge,linux,2.66
us-east-1,i2.xlarge,linux,0.853
us-east-1,i2.2xlarge,linux,1.705
us-east-1,i2.4xlarge,linux,3.41
```

Fig. 4.1 Sample Pricing data from AWS on CSV format, showing region, instance type, operating system, and hourly price

SMC. A simple validating tool we called estimator was developed to test the validity of our extracted data. The estimator tool works similar to the GCP PC and AWS SMC: it prompts user for the cloud platform, the number of instances, operating system, region, instance type, and storage. Then it computes the cost estimates using prices from the extracted data. On AWS SMC the monthly estimated cost was computed for 6 different instance types, located in the US East (Virginia) data center, booted with Linux operating system, with 500 GB of storage for a period of 1 month. The estimated costs were recorded. The same options were selected on the estimator tool and the corresponding results recorded. Figure 4.2 shows the cost estimated for each chosen instance on AWS SMC and estimator tool. The recorded results are tabulated in table A.3. Similarly on GCP PC, the monthly cost of 6 different instances types, located in the US data centers, booted with Linux operating systems and 375 GB of SSD volumes, with 500 GB of storage for period of 1 month. Figure 4.3 shows the estimated monthly cost for each chosen instance on GCP PC and estimator tool. The recorded results are tabulated in table A.4.

The results in figures 4.2 and 4.3 shows that that the extracted pricing data used for estimation of applications' cost on GCP and AWS is correct and up to date.

4.3 Framework Architecture

The framework was designed to be portable and efficient. The architecture consist of two main components: foreign and native components. The architecture employed a

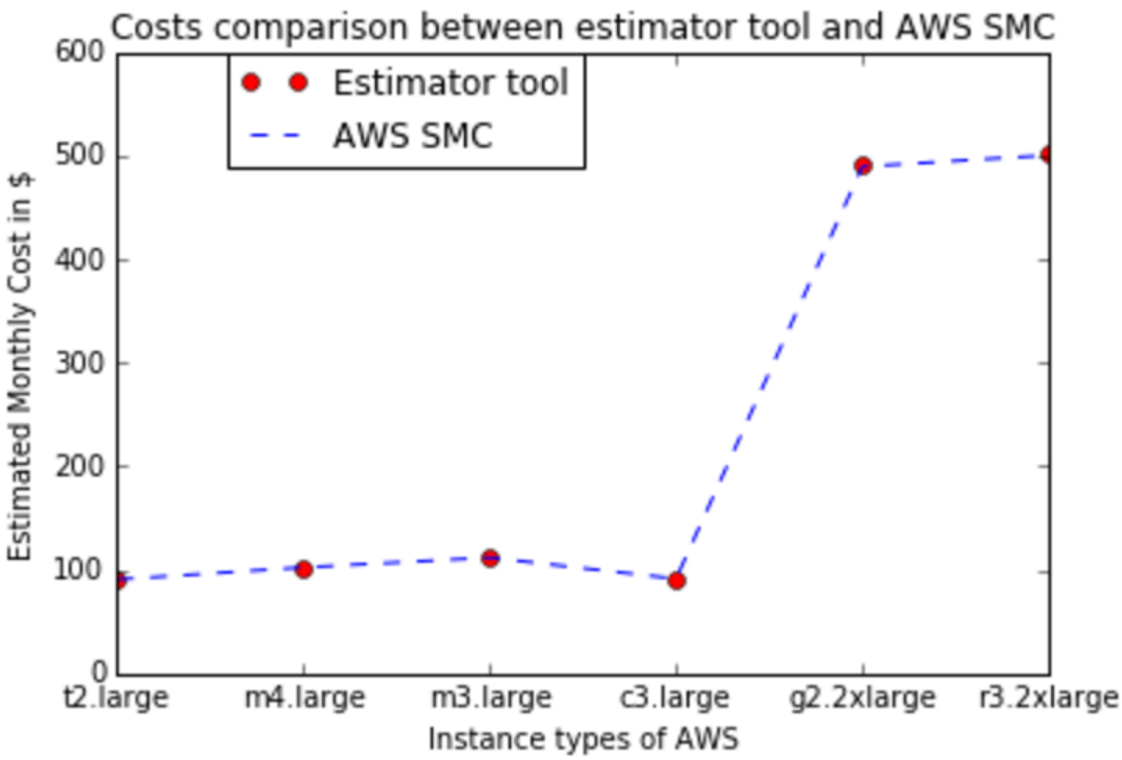


Fig. 4.2 Comparison of cost estimates between AWS SMC & estimator tool

push-based model to register multiple nodes in users' development environment to the framework application. This process is carried out by the foreign components resource miner and resource monitor as shown in figure 4.4.

4.3.1 Foreign Components

These components are regarded external because they are designed to execute on each node of users development environment. The external component consists of the resource miner and the resource monitor. These are python scripts that run on each node on the user's development environment. The resource miner perform the metering activity of the framework and the resource monitor scripts perform the resource monitoring activity of the framework. The resource monitor sends resources usage data (CPU, memory, disk) every 60 seconds to the database whereas the resource miner sends metered data (number of CPU cores, memory size, storage capacity) to the database once.

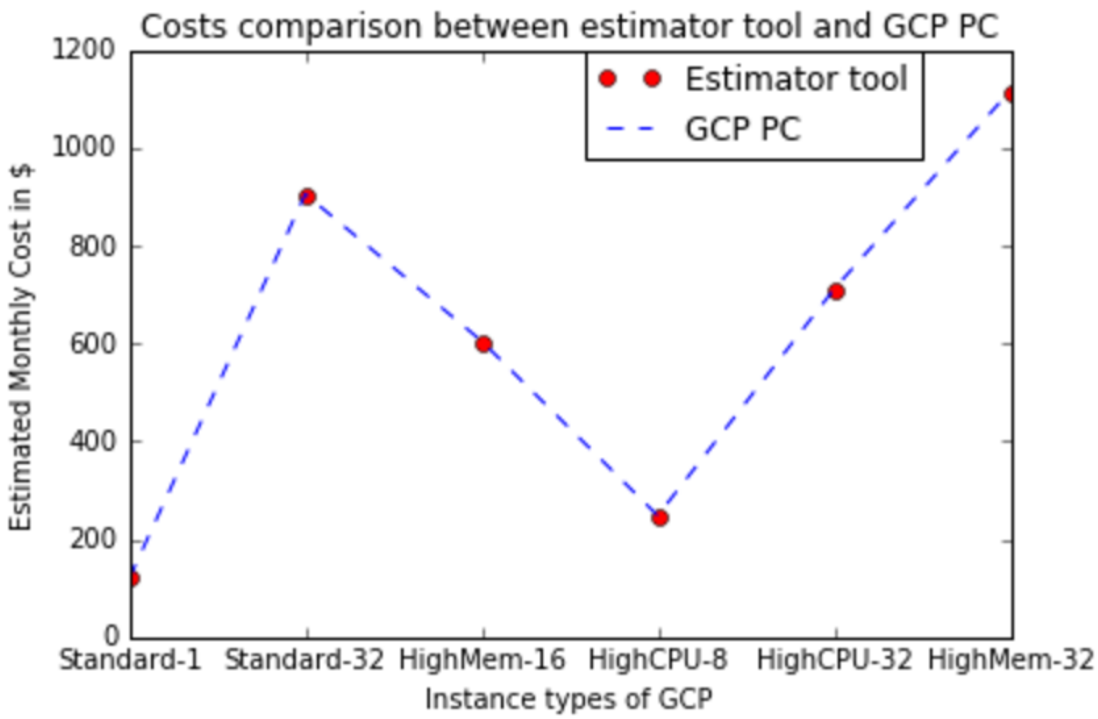


Fig. 4.3 Comparison of cost estimates between GCP PC & estimator tool

4.3.2 Native Components

The native components consists of a database, a python backend implementation, and the Flask application. These component are designed to be deployed on a single node. Although the database could be on a different node, We recommend it to be deployed on the same node as the application framework to avoid any additional use of under-utilized instance. The database is a NOSQL database called MongoDB. It stores the metered data retrieved by the resource miner and the monitoring data that is retrieved by the resource monitor.

The database consist of three collections, first collection stores clusters information, the second collection that stores the metered data and the third stores the resource usage data. The monitored data collection is capped to store a maximum of 2 day of monitored data for 20 nodes in an environment. That means the monitored data collection can not exceed 113 MB of storage. Our database design (See figure 4.5) supports multiple user application development environments. This allow user to see how different applications perform on the public cloud environments. The framework

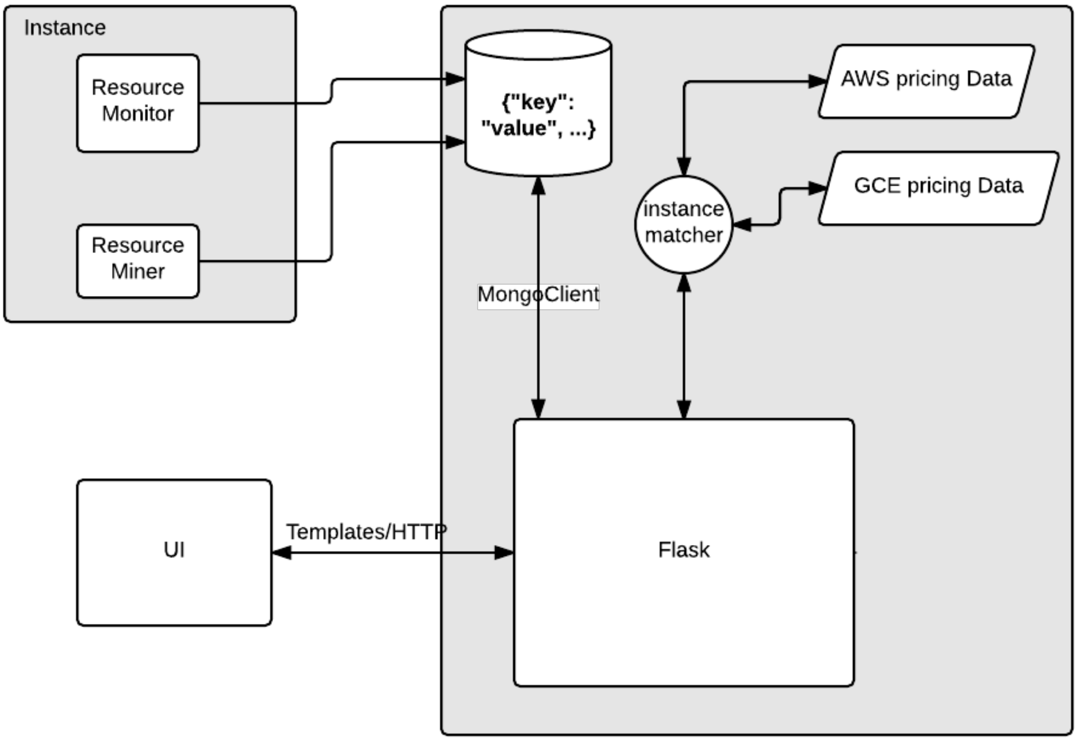


Fig. 4.4 CLOUD-METRIC framework architecture

implementation uses python virtual environment that contains all the required python libraries and dependency frameworks such as Flask and Pymongo[1]. The business logic consists of modules for querying data from the mongoDB, modules for cost computation on AWS and GCP, modules for matching instances to AWS instances types and GCP instance types, and modules for optimization. The Flask micro-framework act as the web server for rendering the user interface for the user.

4.4 Test Environment

On the SNIC cloud, we set up a Hadoop cluster with four nodes of varying capacity – from nodes with 1 virtual cores to nodes with 8 virtual cores – as the test environment. Another flavor was started and set up as the framework development environment where we added a database and the python virtual environment. The framework was tested on the Hadoop cluster which ran one master and four slaves. The resource miner

[1]Pymongo is a Python distribution containing tools for working with MongoDB

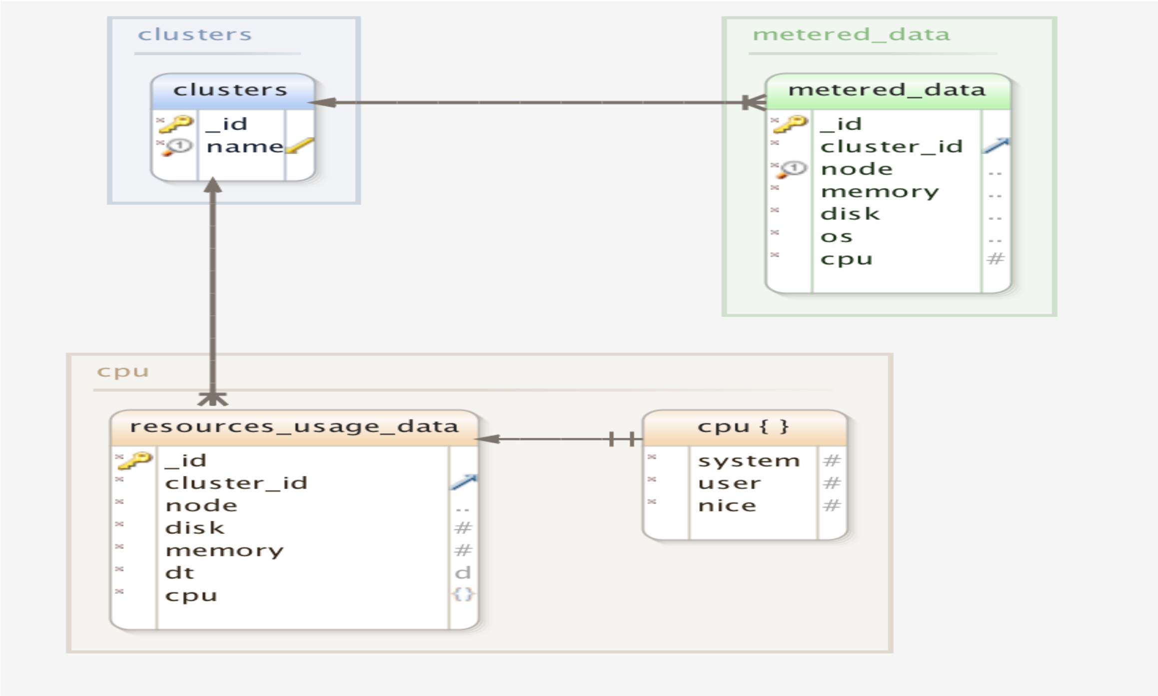


Fig. 4.5 CLOUD-METRIC framework database schema

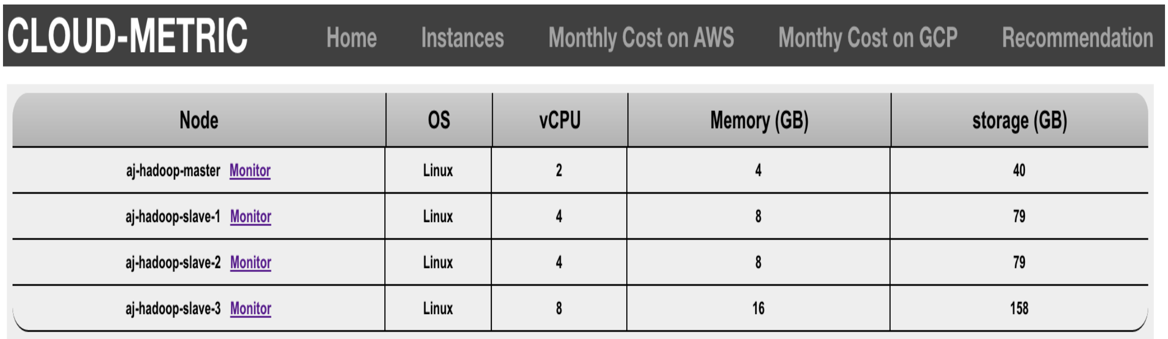
was executed on each of the nodes and the resource monitor was executed as process on each node.

4.5 Framework Functionality

The proposed framework provides functionality that achieved the project goals. The functionality implemented on the framework includes metering of instance resources, cost estimation for cluster on AWS and GCP, monitoring of individual nodes within cluster, monitoring of overall cluster environment, and recommendation for optimized instances type and instance number on both AWS and GCP.

4.5.1 Metering Instance Resources

The metering activity in our proposed framework is carried out by the resource miner, which is an external component of the framework. Each node in the users cluster must ran the resource miner once so that it could be detected by the framework as part of a cluster. The resource miner uses psutil[2] to meter the host name, operating system, number of CPUs, memory size, and disk size of each node and sends the data to the database. In our Hadoop test environment, we have run the resource miner on each of the nodes to allow us to show on the user interface the number of nodes in the cluster and capacity of resources. Figure 4.6 show the nodes in our Hadoop cluster and the capacity of each node's CPUs, memory, and disk storage.



Node	OS	vCPU	Memory (GB)	storage (GB)
aj-hadoop-master Monitor	Linux	2	4	40
aj-hadoop-slave-1 Monitor	Linux	4	8	79
aj-hadoop-slave-2 Monitor	Linux	4	8	79
aj-hadoop-slave-3 Monitor	Linux	8	16	158

Fig. 4.6 List of nodes in Hadoop cluster and their capacity of resources

4.5.2 Cost Estimation

The cost estimation is the principal component of the framework. The framework provides estimated cost for running applications on AWS and GCP. The cost estimation consist of two significant algorithm implementations: The matching algorithm which map nodes to closest matching instances on AWS EC2 and GCP CE, and the cost computation algorithm which implements the formulas outlined in sections 3.3.1 and 3.3.2.

Matching Algorithm

The matching algorithm involves one routine. The routine takes as input, a dictionary data structure that contains instances and their respective resources capacity, the number of virtual CPUs, and memory size of the instance being matched, and return the closest matching instances that is computed based on a matching factor. The instances with the lowest matching factor is returned by each routine as the closest matching instance type. The matching factor is a function of the memory size. Initially

[2]psutil is a cross-platform python library for retrieving system information such a CPU, network, memory

each instance in the data structure has a matching factor of 0 which means every instance in the data structure is a match in terms of memory size. The algorithm scans the data structure and retrieve all instances that match the CPU cores and updates the matching factor of each retrieved instance and finally returns the instance(s) with the lowest matching factor. The generalized matching algorithm is outlined in algorithm 1.

Algorithm 1: get Instances algorithm

```
Data: DictionaryofInstances
Input: numberOfCPUs, MemorySize
Output: List of matching instances
Min ← BIGINTEGER
foreach instanceType in DictionaryofInstances do
    if inputCPU matches instanceType CPU then
        MatchingFactor ← differenceInMemorySizes
        if MatchingFactor < Min then
            Min ← MatchingFactor
        end
        addToCPUMatchingInstance
    end
end
foreach InstanceType in CPUMatchingInstances do
    if matchingFactor = Min then
        addInstanceToList
    end
end
```

Cost estimator

The framework's cost computation consist of 2 routines. One routine implements the cost computation from AWS EC2 and EBS pricing data. The other implements the cost computation on GCE. The cost computation in our framework is similar to that of AWS and GCP in that we have used the same parameters that have significant impact on the cost of instances such number of CPUs, memory size, disk storage. The initial estimate of instances in a cluster takes by default US region for the cost estimation on GCP and US-East-1 region for the cost estimation on AWS. The framework computes only monthly estimates on both GCP and AWS which conforms to the On-Demand (Pay-as-you-go) subscriptions on AWS and GCP. We used regular virtual machines class[3] for monthly estimation on GCP CE instances and On-Demand instances on AWS EC2. The generalized algorithm for the cost computation is outlined in algorithm 2.

Algorithm 2: General cost estimation algorithm

```
Data: PricingData, ComputedMatchingInstances
Input: instanceType, Region, StorageSize, NumberOfInstances,OS,
Output: EstimatedMonthlyCost
data ← readPricingData
uses 30.5 days as average number of days in month
monthHours ← (30.5 ∗ 24)
totalCost = 0
if instanceType in data then
    instanceHourlyCost ← data[region][instanceType]
    instanceMonthlyCost ← NumberOfInstances ∗ instanceHourlyCost ∗
    monthHours
    osHourlyCost ← data[os]
    OSCost ← NumberOfInstances ∗ osHourlyCost ∗ monthHours
    storageCost ← data[region][storage] * StorageSize
    totalCost ← OSCost + instanceMonthlyCost + storageCost
end
```

Cost estimates on Individual Nodes and Cluster: The framework provides users the functionality to estimate cost of individual nodes in the cluster as well as the overall cluster for maximum utilization in a month. The overall cluster cost estimation is the sum total of individual instances cost on the default regions – US data centers. The framework provides users interface to see differences in cost of instances in all regions on both AWS and GCP. Figures 4.7 and 4.8 show the cost of running our Hadoop cluster on AWS and GCP respectively. Figures 4.9 and 4.10 show the various estimated cost for running the master node of our Hadoop cluster in different regions on AWS and GCP respectively.

AWS and GCP On-Demand Cost Estimates: The results of the cost estimation showed a huge difference between the monthly cost of our Hadoop cluster on AWS and the monthly of the cluster on GCP. This huge difference is because GCP

[3]Google Cloud platform provides two virtual machines (VM classes: Regular and Preemptible. The difference is that latter is short lived and suitable for fault tolerant applications and lasts for up to 24 hours whereas the former runs until terminated by user.

Node	Cost estimate per month
aj-hadoop-master	$39.14
aj-hadoop-slave-1	$155.63
aj-hadoop-slave-2	$155.63
aj-hadoop-slave-3	$310.53

Total Estimated Cost of Cluster **$660.93 / Month**

Fig. 4.7 Estimated Cost of Hadoop Cluster on AWS

Node	Cost estimate per month
aj-hadoop-master	$26.24
aj-hadoop-slave-1	$52.45
aj-hadoop-slave-2	$52.45
aj-hadoop-slave-3	$104.91

Total Estimated Cost of Cluster **$236.06 / Month**

Fig. 4.8 Estimated Cost of Hadoop Cluster on GCP

provides an automatic discount on the hourly charges of virtual machines for every additional minute of machine usage on top of the initial 25% usage in a month. This discount scheme called Sustained Usage Discount is discussed in detail in section 3.3.2. AWS, on the other hand, charges a fixed hourly cost for each virtual machine for every hour of usage in a month. The framework incorporated these on-demand subscription discounts in its cost computation algorithm. We have provided users the interface to see how the hourly unit cost of instances changes over a monthly period of utilization. In figure 4.11, we visualized the variation on the hourly charges for `c3.xlarge` on AWS and `N1-HighCPU-4` on GCP over several percentage of usage in a month. Both `c3.xlarge` and `N1-HighCPU-4` are closest matching instances for the master node (4 vCPUs and 8 GB of memory) of our Hadoop test environment.

Cost of aj-hadoop-master in AWS regions

Region	Cost Estimate per Month
US-EAST-1	$39.14
US-WEST-1	$50.94
US-WEST-2	$39.14
EU-WEST-1	$42.06
AP-SOUTHEAST-1	$59.58
AP-SOUTHEAST-2	$59.70
AP-NORTHEAST-1	$59.70
SA-EAST-1	$80.44
EU-CENTRAL-1	$45.08
US-GOV-WEST-1	$45.26

Fig. 4.9 Estimated Cost of master AWS regions

Cost of aj-hadoop-master in GCP regions

Region	Cost Estimate per Month
US	$26.24
EUROPE	$28.76
ASIA	$28.76

Fig. 4.10 Estimated Cost of master node on GCP regions

4.5.3 Resource Monitoring

The monitoring aspect of the framework provides the the ability to visualized the performance of each node in the cluster and the overall cluster. The parameters we monitor in each node are CPU, memory, and disk. The monitoring data is used in the implementation of the optimization which is discussed in section 4.5.4.

Single Node monitoring

For each node in our Hadoop[4] cluster, there is a resource monitor process that sends CPU, memory, and disk usage data to the database every 60 seconds. The stored data

[4]Hadoop is a framework that allows for the distributed processing of large data sets across clusters of computers

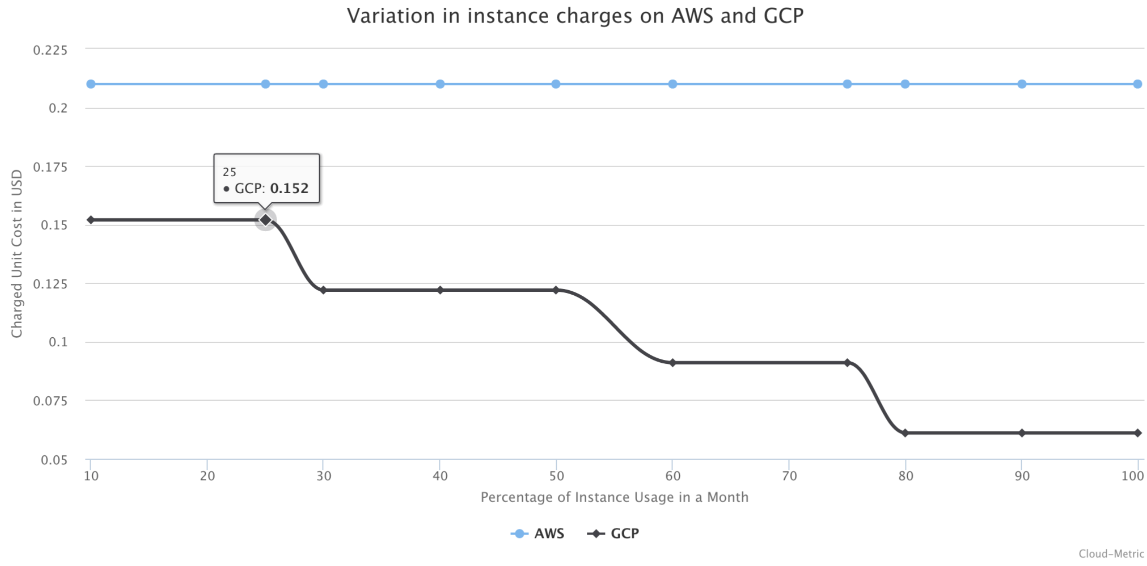


Fig. 4.11 Variation of hourly instance charges on AWS and GCP

is retrieved via a MongoClient[5] API and displayed on the framework user interface. Figure 4.12 shows integrated visualization of monitoring resources (CPU, memory, disk) data of individual node.

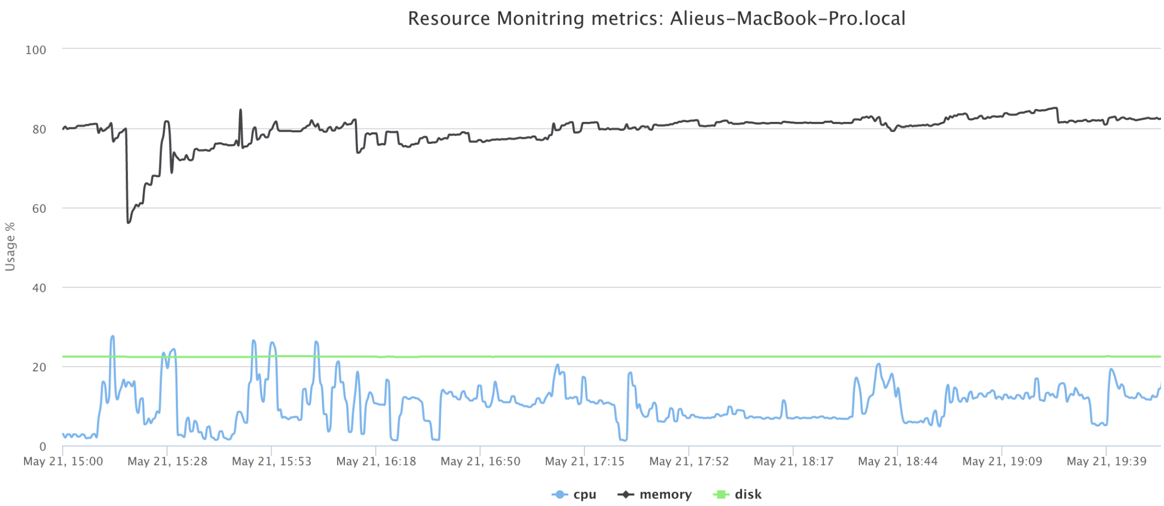


Fig. 4.12 Visualization of CPU, memory, and disk utilization on an individual node

[5]A python class that provides API for connecting to MongoDB

Cluster Monitoring

The user is provided with the functionality within the framework to visualize the overall performance of an entire cluster. In this case, the stored data of the nodes' resources (CPU, memory, and disk) is grouped on hourly basis and the average is taken for each of CPU, memory, and disk usages. The monitoring charts display the percentage usage against the hourly utilization of the entire cluster. Figure 4.13 shows an integrated visualization of the CPU, memory, and disk usage of an our Hadoop cluster.

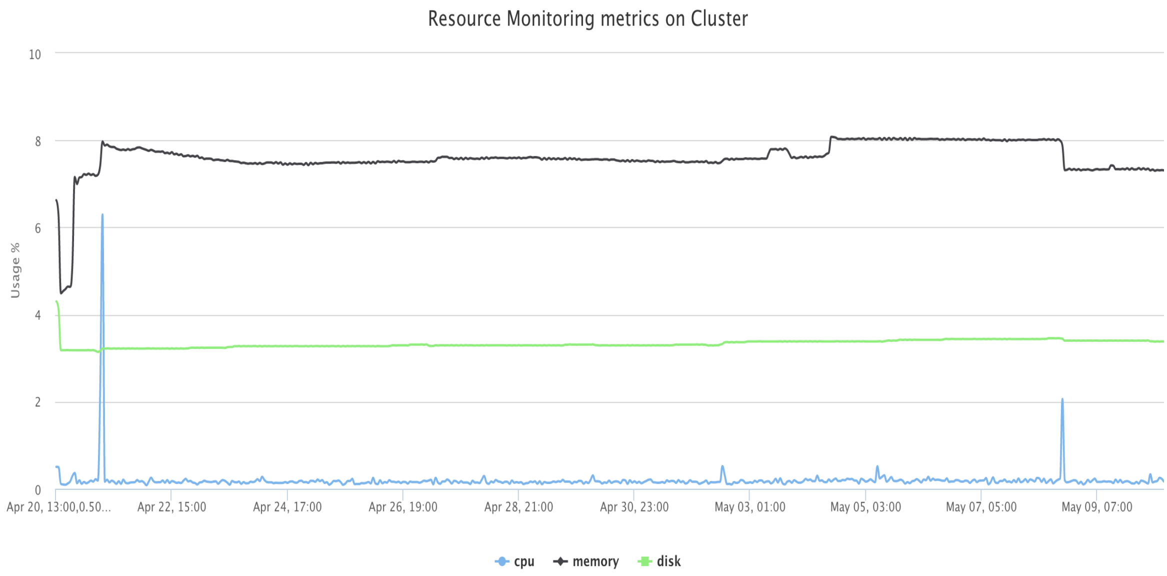


Fig. 4.13 Visualization of resources usage on Hadoop cluster

4.5.4 Instances Recommendation

The framework recommends for users instances on AWS and GCP that match resources usage of the cluster over a period of time. The recommended instances are result of an optimization algorithm that creates a machine type from the resources utilization of a node in user environment over a period of time. Since the database stores just above 5MB of resource utilization data, the time period the algorithm consider for resource utilization is maximum of 2 days. The algorithm queries for average CPU and memory utilization and construct an instance from the data retrieved. The constructed instance is then matched with similar instance on AWS and GCP via matching algorithm outlined in section 4.5.2. In addition, the costs of the matching instances on AWS and GCP are computed via the cost estimation algorithm in section 15. Detail of the recommendation algorithm is outlined in algorithm 3.

We have tested the recommendation algorithm on a 2-node cluster with two test cases, which is outlined in chapter 5

Algorithm 3: Recommendation algorithm

Data: Resource Utilization Data, Pricing Data, Instances Types on AWS and GCP, Cluster

Output: Recommended Instances, EstimatedMonthlyCost of Recommended Instances

```
foreach Node in Cluster do
    retrieve CPU, memory, disk, OS
    retrieve average CPU and Memory Utilisation
    compute CPU and memory size from utlilization
end
foreach Computed CPU, Memory do
    get matching instances on AWS
    get matching instances on GCP
end
foreach Matching Instances do
    Compute cost of instance in AWS
    Compute cost of instance in GCP
end
```

Chapter 5

Framework Evaluation

We have proposed a portable framework that would not consume much of users compute resources. To validate that, we have evaluated the resources utilization of both the external (resource monitor) and internal (application and database) components of the framework. The evaluation process for each of the framework components was carried out with `nmon`[1] – read and store resource utilization data – and NMON Visualizer[2] – visualizes stored data in charts.

In the following sections, we will present the result of our evaluation of each of the framework components – recommendation algorithm, resource monitor, database, and application.

5.1 Recommendation Algorithm

We have evaluated our recommendation algorithm using 2-node cluster. Each of the nodes has 8 vCPUs and 16G of memory. We tested the performance using the following cases: ran basic Hadoop jobs and stress CPU for maximum utilization.

5.1.1 Basic Hadoop jobs

Initially, we set up the cluster and decided not to run any resource intensive jobs. We ran the Hadoop jobs and our monitoring process on each node. Each node initially matched `c4.2xlarge` instance on AWS EC2 and `N1-HighCPU-8` on GCP CE. You will see

[1] nmon is a Linux performance and resources monitoring tool
[2] A jar file developed purposely for nmon data visualization

detail of the instances on AWS and GCP in appendix A. The algorithm recommended `c3.xlarge` and `N1-HighCPU-4` for each node on AWS and GCP respectively. The recommended instances have 4 CPUs, that is half of the number of CPUs on each node in the cluster. There is a cost reduction of about 50% on the recommended cost. (See figure 5.1).

5.1.2 Stress CPU for maximum usage

On each node in the cluster we ran 8 CPU-intensive processes to maximize CPU usage for a period of 8 hours. Each process is the following command which utilizes a single core 100%: `$ yes > /dev/null &`. The recommendation algorithm recommended `c4.2xlarge` for AWS and `N1-HighCPU-8` (See figure 5.1) for each of the nodes in the cluster. In this case, the algorithm recommends the actual static matching instances for the CPUs were maximally utilized.

Instances Recommendation

Our optimizer has performed a resources scan on your cluster and recommend that you use the following instances on AWS and GCP for your cluster.

Instance Types on AWS	Machine Types on GCP
C3.XLARGE	N1-HIGHCPU-4
C3.XLARGE	N1-HIGHCPU-4

Instance Types on AWS	Estimated Monthly Cost	Instance Types on GCP	Estimated Monthly Cost
C3.XLARGE	$161.62	N1-HIGHCPU-4	$84.20
C3.XLARGE	$161.62	N1-HIGHCPU-4	$84.20

Total Estimated Cost $323.24 / Month   Total Estimated Cost $168.41 / Month

(a) Output of recommendation on case 1

Instances Recommendation

Our optimizer has performed a resources scan on your cluster and recommend that you use the following instances on AWS and GCP for your cluster.

Instance Types on AWS	Machine Types on GCP
C4.2XLARGE	N1-HIGHCPU-8
C4.2XLARGE	N1-HIGHCPU-8

Instance Types on AWS	Estimated Monthly Cost	Instance Types on GCP	Estimated Monthly Cost
C4.2XLARGE	$314.61	N1-HIGHCPU-8	$162.09
C4.2XLARGE	$314.61	N1-HIGHCPU-8	$162.09

Total Estimated Cost $629.22 / Month   Total Estimated Cost $324.18 / Month

(b) Output of recommendation on case 2

Fig. 5.1 Instances recommended by our recommendation algorithm on two test cases

5.2 Resource Monitor

Since the resource monitor scripts is executed every 60 seconds on each user node, we expect close to negligible resources (CPU, memory,and network) utilization. To validate our expectation, we used nmon to store resources utilization data in CSV file for a period of 24 hours. We ran the following command which captures resources utilization including top processes every 20 seconds for a total count of 4320, that is $24hrs$ hours, on the master node of our Hadoop cluster.

```
$ nmon -ft -s 20 -c 4320
```

Figure 5.2 show the CPU utilization of our resource monitor python process. The data was visualized with nmon Visualizer.

The data visualized confirmed that our resource monitoring process has an very low CPU utilization: maximum of 0.001 over a period of 24 hours.

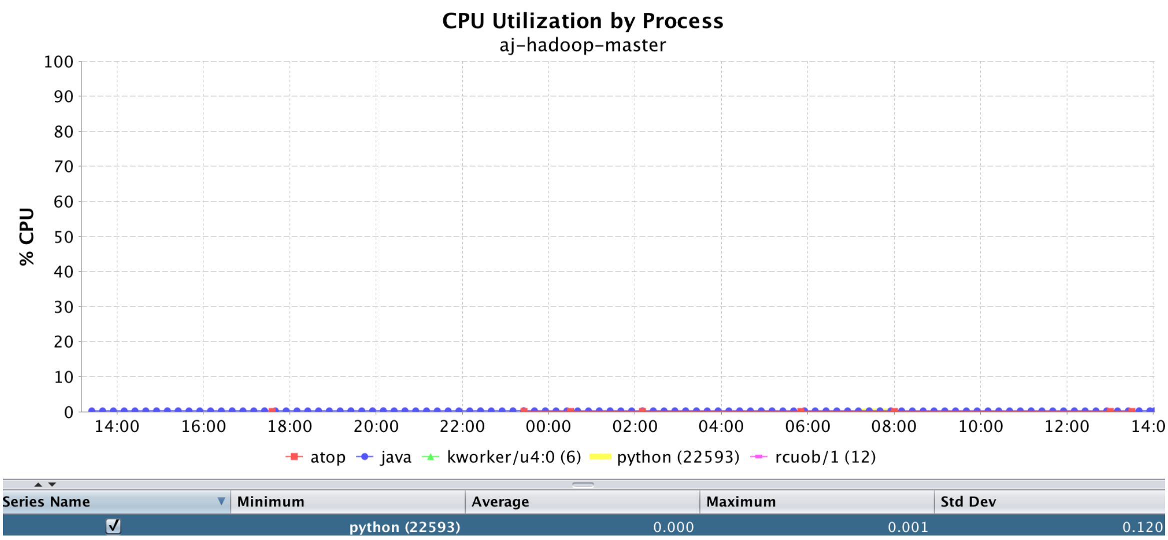


Fig. 5.2 Visualization of resources monitor CPU usage on Hadoop cluster master node

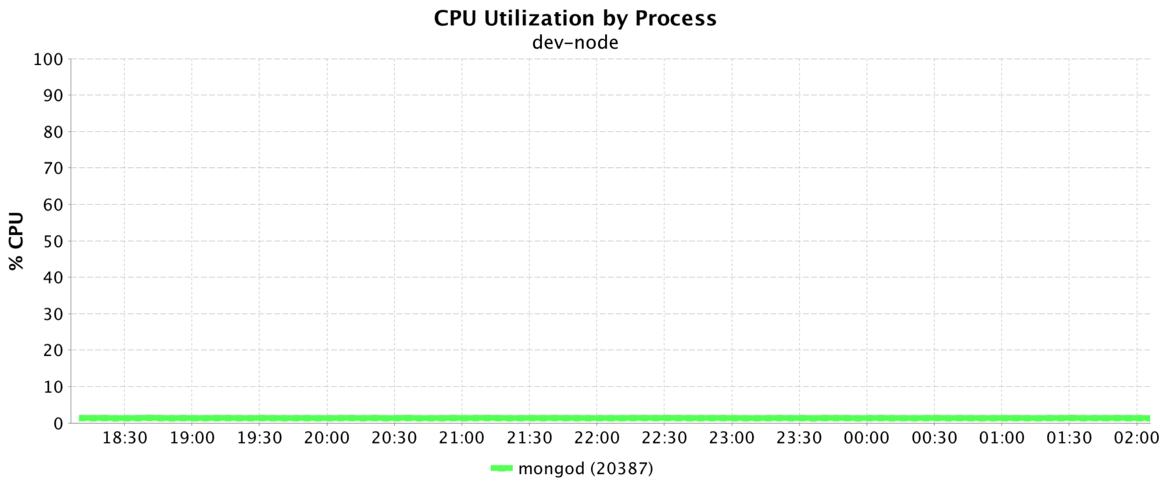
5.3 Database

We evaluated the CPU, memory, and disk utilization on the node that hosted the framework mongoDB database using the nmon tool for 8 hours. The node had only the mongoDB running. We ran the nmon command – `nmon -ft -s 2 -c 14400` – which records resources utilization of processes every 2 seconds for 8 hours. We ran the application and accessed the interface while the nmon process records the resource utilization data. The mongoDb process recorded a maximum CPU utilization of just above 2%. Figures 5.3a, 5.3b, 5.3c) show the CPU, memory and and disk utilization over the period.

5.4 Application

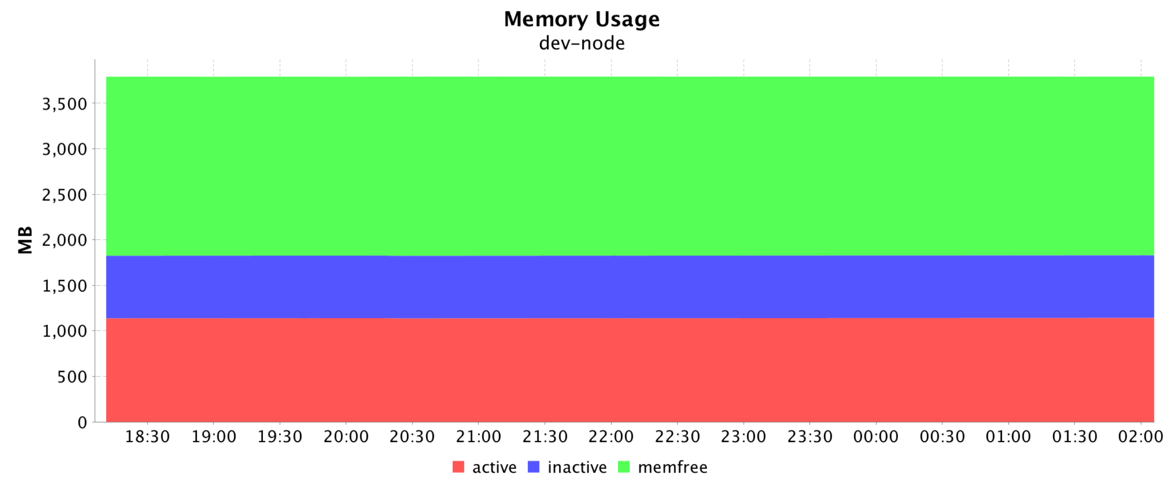
To evaluate how our application consumes compute resources, we started a `t1.micro` instance (free tier) on AWS EC2 on EU-WEST-1 region and deployed the application on the instance. We ran the nmon command – `nmon -ft -s 2 -c 14400` – which records resources utilization of processes every 2 seconds for 8 hours. Within the period, we access the application from our browsers for a about 1 hour.

As shown in figure 5.4 the application process (python) recorded a maximum CPU usage of 3.490. The memory utilization, which occurs as a result of the execution of the algorithm within the business logic and data structures of the application, showed a maximum active memory of 286.3MB within the 8 hour period. The network utilization results from the queries from the database, which was hosted in the SNIC cloud, and the HTTP requests from our browsers, showed a maximum read and maximum write of 119.571 KB per second and 5.658 KB per second respectively.



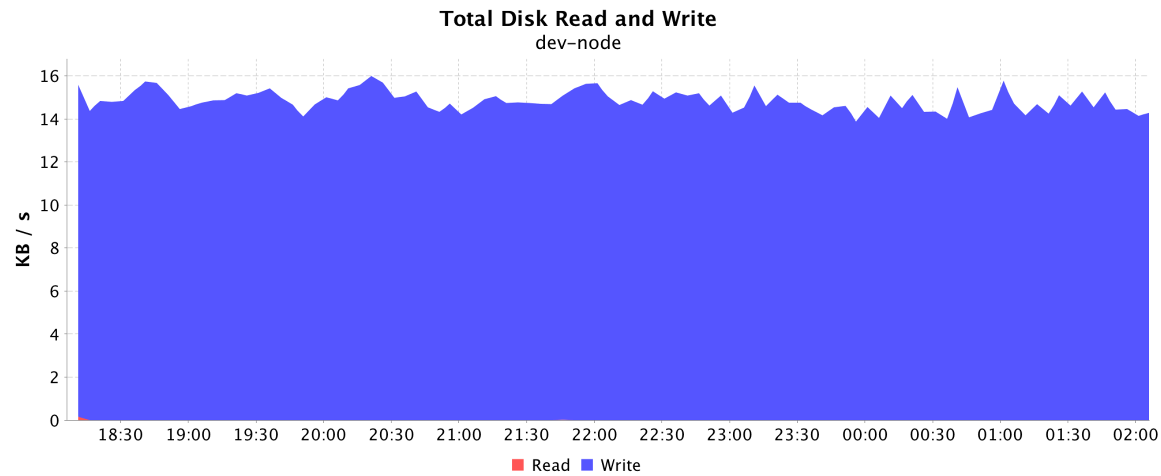
	Series Name	Minimum	Average	Maximum	Std Dev
☐	rcuob/1 (12)	0.000	2,000,996,690,471,42...	2,881,435,234,278,851...	75,906,115,562,874,4...
☑	mongod (20387)	0.000	1.362	2.275	0.279

(a) mongoDB's CPU utilization on host



Series Name	Minimum	Average	Maximum	Std Dev
active	1,135.900	1,138.634	1,143.200	1.551

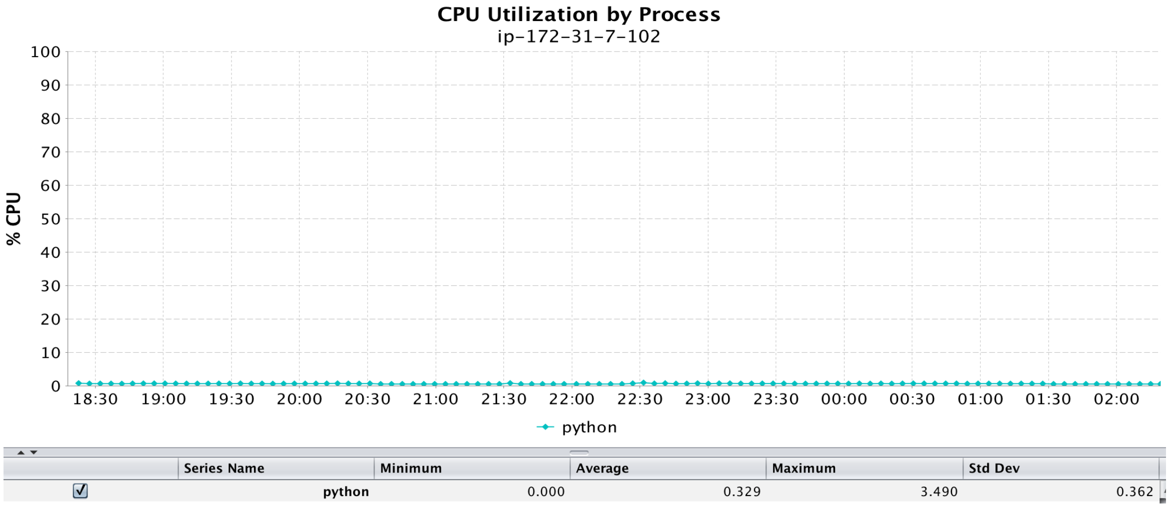
(b) mongoDB's memory utilization on host



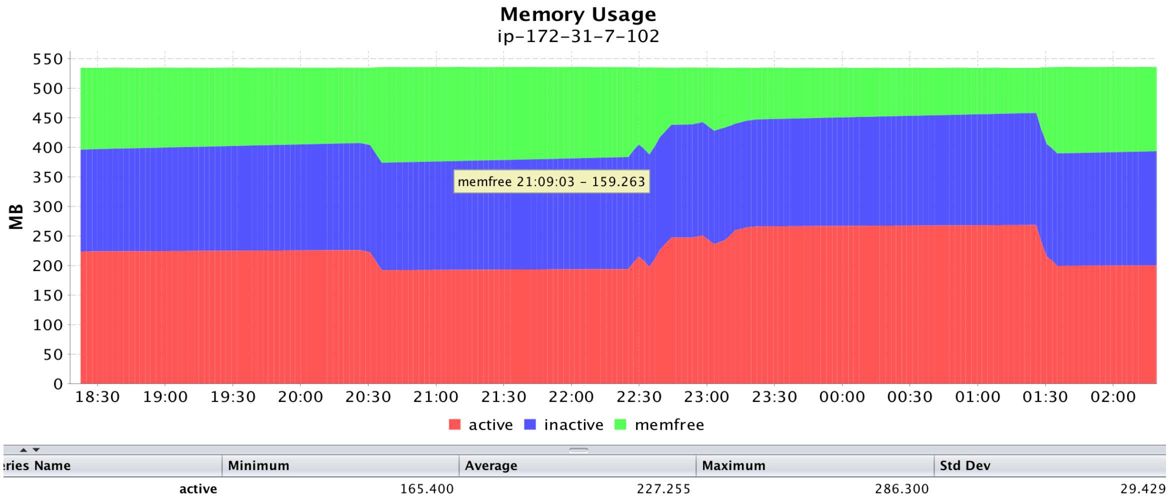
Series Name	Minimum	Average	Maximum	Std Dev
Read	0.000	0.002	2.500	0.066
Write	3.800	14.844	35.800	7.049

(c) mongoDB's disk writes on host

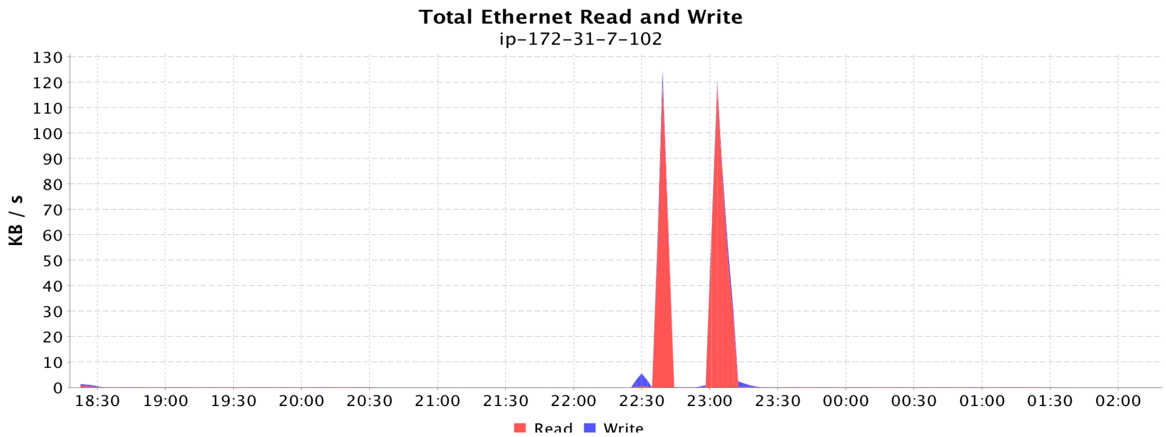
Fig. 5.3 Resources utilization of database



(a) Application's CPU utilization



(b) Application Memory utilization



(c) Application network read and write

Fig. 5.4 Resources utilization of the framework application

Chapter 6

Conclusion and Future Work

We have proposed and developed CLOUD-METRIC as lightweight and portable framework that extends the classic application development model with cloud infrastructure execution cost, better estimates of required resources, and recommendation for about execution plan. Primarily, the framework provides estimated monthly cost of running applications on AWS and GCP. The framework provides the ability to monitor development environment both for single node and entire cluster to assess resources utilization which also provides the basis for the recommendation of instances types on AWS and GCP.

The framework is designed to be pluggable to any development environment or research environment. It is a third party tool that developers could add to their development environment to provide cost estimates of an application in development phase. In addition, researchers within the scientific community that consider leveraging public clouds infrastructures such as GCP and AWS as result of limited resources in private academic cloud deployments such as Uppmax at Uppsala University could utilize the framework to get estimates of cost running similar workloads in the AWS and GCP.

6.1 Future Work

It would be interesting to incorporate a learning algorithm in the instance recommendation that recommend the number of instances and instance types based on resource utilization and additional parameters such as application specific requirements such memory intensive, CPU intensive, storage intensive. In this case the algorithm would learn from data from public cloud providers about different instance types and scan the user's application environment and identify it as either CPU intensive, memory intensive or data intensive labels. This would provide a much more perfect recommendation between applications and the instance types. Another interesting thing would be to defined a model that tell the recommendation algorithm the condition for scaling in and out the number of instances the user have in their environment for optimal performance and lowest cost possible. In addition, the framework could be enhanced to include the consideration of more details chargeable parameters that are used in billing systems of public cloud providers, such as number of elastic IPs, number of load balances, Data Ingress and Egress. Another further improvement would be to provide support for other cloud providers such as Microsoft Azure, and Rackspace.

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Appendix A

Table A.1 List of AWS instance Types and associated resource capacity obtained from [1]

	vCPUs	ECU	Memory (GB)
General Purpose			
t2.nano	1	variable	0.5
t2.micro	1	variable	1
t2.small	1	variable	2
t2.medium	2	variable	4
t2.large	2	variable	8
m4.large	2	6.5	8
m4.xlarge	4	13	16
m4.2xlarge	8	26	32
m4.4xlarge	16	53.5	64
m4.10xlarge	40	124.5	160
m3.medium	1	3	3.75
m3.large	2	6.5	7.5

m3.xlarge	4	13	15
m3.2xlarge	8	26	30
Compute Optimized			
c4.large	2	8	3.75
c4.xlarge	4	16	7.5
c4.2xlarge	8	31	15
c4.4xlarge	16	62	30
c4.8xlarge	36	132	60
c3.large	2	7	3.75
c3.xlarge	4	14	7.5
c3.2xlarge	8	28	15
c3.4xlarge	16	55	30
c3.8xlarge	32	108	60
GPU instances			
g2.2xlarge	8	26	15
g2.8xlarge	32	104	60
Memory Optimized			
r3.large	2	6.5	15
r3.xlarge	4	13	30.5
r3.2xlarge	8	26	61
r3.4xlarge	16	52	122
r3.8xlarge	32	104	244
Storage Optimized			

i2.xlarge	4	14	30.5
i2.2xlarge	8	27	61
i2.4xlarge	16	53	122
i2.8xlarge	32	104	244
d2.xlarge	4	14	30.5
d2.2xlarge	8	28	61
d2.4xlarge	16	56	122
d2.8xlarge	36	116	244

Table A.2 List of GCE Machine Types and associated resource capacity as obtained from [2]

Machine Type	Virtual CPUs	Memory	GCEU
Standard Machine Types			
n1-standard-1	1	3.75GB	2.75
n1-standard-2	2	7.5GB	5.50
n1-standard-4	4	15GB	11
n1-standard-8	8	30GB	22
n1-standard-16	16	60GB	44
n1-standard-32	32	120GB	88
Shared-Core Machine Types			
f1-micro	1	0.60GB	Shared CPU

g1-small	1	1.70GB	1.38
High Memory Machine Types			
n1-highmem-2	2	13GB	5.50
n1-highmem-4	4	26GB	11
n1-highmem-8	8	52GB	22
n1-highmem-16	16	104GB	44
n1-highmem-32	32	208GB	88
High CPU Machine Types			
n1-highcpu-2	2	1.80GB	5.50
n1-highcpu-4	4	3.60GB	11
n1-highcpu-8	8	7.20GB	22
n1-highcpu-16	16	14.40GB	44
n1-highcpu-32	32	28.80GB	88

Table A.3 Results of Cost estimated obtained from AWS Simple Monthly Calculator and Estimator tool for selected instances

	t2.large	m4.large	m3.large	c3.large	g2.2xlarge	r3.2xlarge
AWS SMC	$90.67	$102.35	$111.84	$91.40	$489.25	$500.20
Estimator tool	$90.98	$102.69	$112.21	$91.70	$490.68	$501.63

Table A.4 Results of Cost estimated obtained from GCP Pricing Calculator and Estimator tool for selected machine type

	standard-1	standard-32	highMem-16	highCPU-8	highCPU-32	highMem-32
GCP PC	$119.35	$905.20	$605.06	$248.13	$710.51	$1116.11
Estimator tool	$119.95	$901.15	$602.78	$247.97	$707.61	$1110.81