Chapter 1

Introduction

1.1 Problem Statement

Cloud computing is a computing model offers a network of servers to their clients in a on-demand fashion. From NIST's definition [**?**], *"cloud computing 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."*

Cloud computing has completely reformed the software industry [2] by providing three major benefits to web-based software or web service providers. First, service providers do not need upfront investment in hardwares (e.g servers and networking devices) and pay for hardwares' maintenance. Second, service providers will not worried about the limited resources will obstruct the performance of their services when unexpected high demand occurs. The elastic nature of cloud can dynamic allocate and release resources for a service. In addition, software providers can pay as much as the resource usage under a *pay-as-you-go* policy. Third, service providers can publish and update their applications at any location as long as there is an Internet connection. These advantages allow anyone or organization to deploy their softwares on Cloud in a reasonable price.

From Cloud providers' perspective, they are trying to make the most profit on data centers. On one hand, cloud providers are trying to improve the quality of Cloud service to attractive more service providers migrate their business to Cloud. On the other hand, they want to cut enormous energy consumption - as much as 25,000 households [8] - to lower the expense.

Energy consumption in data centers are derived from several parts as illustrated in Figure 1.1. Regardless the energy consumption of refrigeration system (or cooling system), the majority of energy consumption are from servers. According to Hameed et al [6], servers are far from energy-efficient and the main reason for its wastage is "the idle power when ICT resources such as servers providing computing and storage capacities run at low utilization". Therefore, a concept of *energy proportional computing* [1] raised to address the low utilization and it leads to the vitualization technology and server consolidation.

Virtualization [18] partitions a physical machine's resources (e.g. CPU, memory and disk) into several isolated unit called virtual machines (VMs) where each VM allows an operating system running on them. It rooted back in the 1960s' and was invented to enable isolated software testing. Soon, people realized it can be a way to improve the utilization of hardware resources. Thereafter, a resource management strategy of server consolidation was invented.

Server consolidation [21] resolves the low utilization problem by gathering virtual machines (VMs) into a fewer number of physical machines (PMs), so that the resource utiliza-

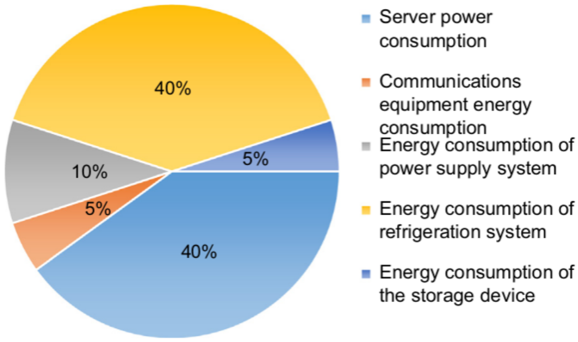

Figure 1.1: Energy consumption distribution of data centers [15]

tion of PMs are maintained at a high level. In the meanwhile, idle servers are turned off to save energy.

Despite the usefulness of server consolidation, it is a difficult task. Server consolidation is often considered as a global optimization problem where its goal is to minimize the energy consumption. From mathematical model's point of view, it is often modeled as a bin-packing problem [11]. Bin-packing problem is a well-known NP-hard problem meaning it is unlikely to find an optimal solution of a large problem. Previous research have studied the problem extensively. Because of its NP-hard nature, deterministic methods such as Integer Linear Programming [16] and Mixed Integer Programming [**?**] are unsuitable for a large scale problem because of the long computation time. More research proposed heuristic methods to approximate the optimal solution such as First Fit Decreasing (FFD) [14], Best Fit Decreasing (BFD) [20]. In addition, manually designed heuristics are designed to tackle the special requirements such as [9, 5, 7]. Although these greedy-based heuristics can quickly solve the consolidation problem, As Mann's research [11] shown, server consolidation is a lot more harder than bin-packing problem - because of multi-dimension, many constraints - therefore, these greedy-based heuristics can not reach a good approximation and be easy to stuck at a local optima.

In addition, virtualization technology has evolved to allow finer granularity resource scheduling. A recent advent of Container technique [**?**] has drove the attention of both industrial and academia. Container is an operating system level of virtualization which means containers share the kernel within a VM and provide isolated environment for applications. This new concept starts a new service model called Container as a Service (CaaS) [**?**] is derived from Platform as a Service (PaaS). In comparison with traditional models, CaaS gives the responsibility of application deployment and resource allocation to the same hand of Cloud provider. Hence, Cloud providers have a better control of their resources, however the management difficulty also increases. Currently, vast amount of research on VM-based data center can not be directly used on Contained-based model. This thesis, therefore, aims at providing an end-to-end solution the contained-based server consolidation problem.

1.2 Motivation

The motivation for this thesis mainly includes two parts, in the first part, we illustrate three roots of container-based server consolidation problem. In the second parts, we explain the motivations for solving the sub-problems of the problem.

- Container is a new virtualization technology which provides an operating level of virtualization. Figure 1.2 illustrates the root of container technology from an energy effi-

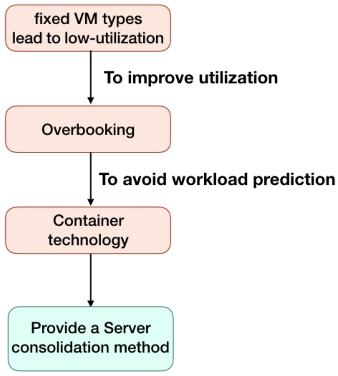

Figure 1.2: The root of container technology

cient point of view. Most Clouds provide a set fixed types of VM for service providers to choose. Each type of VM represents a certain amount of resources (e.g. CPU, RAM, and Storage). This service model leads to a great waste of resources for two reasons. Firstly, service providers tend to over estimate the resources for ensuring the QoS at the peak hours, hence, they often reserve more resource than they need[**?**]. Secondly, specific types of application may use a type of resources a lot more than another [17], for example, computation intensive tasks consume CPU much more than RAM; a fixed type of VM may provides much more RAM than it needs. In order to solve this problem, overbooking strategy tends to place more VMs than the server's maximum capacity. However, this technique is highly relied on the workload prediction running in a VM. Otherwise, servers are easily overloaded. Container technique can improve the utilization by further partitioning VM into resource isolated chunks. Therefore, multiple applications can share the same VM. This technique avoids the prediction of workload as well as improving the utilization. However, it also need consolidation technique to ensure the high utilization.

- This container-based Cloud certainly brings many advantages to current Cloud [**?**]. However, it also brings difficulties for server consolidation. Server consolidation problems are typically modeled as vector bin-packing problem which are NP-hard. Container-based server consolidation add another level of abstraction which makes it a two-level vector bin-packing problem. Current server consolidation methods are mostly VM-based which can not be directly applied on this problem, because two-level of bin-packing problems are interact with each other. Piraghaj [**?**] proposes a two-step procedure, mapping tasks to VMs and allocation of VMs. As Mann illustrated in [12], these two steps should be conducted simultaneously, otherwise it leads to local optimal. Other research [] propose greedy-based heuristics on this problem. They are relatively fast in execution, but they can be easily stuck at local optimal.

Traditional Cloud computing offers three services models: Infrastructure as a Service (IaaS), Platform as a Service (PaaS) and Software as a Service (SaaS). Both IaaS and PaaS describe how does a service provider use the cloud resources. The main difference of these two models are IaaS allows service providers to manage the low-level details including the operating system and libraries. While, PaaS provides a higher level of abstraction where users only focus on the application development without caring the underlying operating system and system-level of resources such as CPU cores and memories. However, one drawback of PaaS is that cloud users must make sure their applications are complete compatible with the platform. And in many of the cases, it is not the situation. In order to solve this problem, a container-based virtualization technology starts to reform the Cloud industry. Container as a Service (CaaS) is a new concept but it has been used in industry for many years. Containers provide an operating system-level of isolation environment for applications. It does not need a hypervisor but complete rely on the operating system.

This exciting new technology has bring so many advantages for both Cloud users and Cloud providers. From the providers' perspective, In a large system, running VMs means there are probably many same operating systems occupying memories and storages. Lightweight containers share operating system and therefore, there are more rooms for softwares. It increases the capability of Cloud data centers. Furthermore, in terms of resource utilization, it provides much finer granularity operation than a VM-based Cloud model. Containers partition a VM into smaller chunks so that with appropriate management, better energy efficiency can be achieved. From the cloud users' perspective, each container provides separated libraries for specific application. Therefore, it does not contrained by the underlying platform. Like PaaS, Cloud users do not need to concern the scalability of applications. Therefore, CaaS can potentially become one of the main stream in the future Cloud computing industry.

Secondly, energy-efficent computing has been the major concern since the begining of computers. Specifially, Cloud computing has become a popular form. Large-scale data centers have been built around the world. A data center can consume huge amount of energies and it needs to improve its energy-efficiency from multiple perspectives. As we discussed in the Introduction, computing servers are one of the major contribution to the energy consumption. And according to observation by [], the average utilization resource are still very low which causes huge energy wastage. As we mentioned above, the container technolgy provides a better way of managing resources, it has the potential to largly improve the utilization than current VM-based Cloud model because it avoids some of the major drawbacks of VM-based model.

Thirdly, because the container technology is relatively new, previous research are mostly focus on IaaS model and so that the server consolidation has based on the VM-level. However,

Frist is this new technology of container that can potentially change the landscape of Cloud computing. It has so many benefits but also it brings difficulty in managing resources.

Second, from green computing point of view, we still need to manage resource so that, the data centers consume less energy. And container technolgy actually bring a better chance to be more energy-efficient than previous VM based technology. Third, it is very difficult to manage this container-based resources because of the problem-nature is too complicated. And existed algorithms can not be directly applied on it. Fourth, the evolutioanry computation provides a good framework to handle such difficult problem.

The disadvantage of tranditional IaaS model has been discovered in the recent years [12]. In IaaS, on one hand, cloud customers need to manage the low-level details ranging from application capacity estimation, resource planning and selection and deployment. On the other hand, Cloud providers manage resource provisioning and allocation. Although these two tasks are seemingly different,

The container as a Service (CaaS) cloud model has gain increasing attention in the recent years. However, the energy efficiency in CaaS cloud environment has not been investigate. Particularly, the virtual machine and container joint consolidation is the core problem. Therefore, in this thesis, we will focus on the end-to-end energy-aware server consolidation on container-based Cloud. In the meanwhile, a major research direction of large scale server consolidation is also considered. The end-to-end server consolidation refers to the server consolidation techniques used in the different stages throughout the routine Cloud resource management including initial VM provisioning and placement, dynamic VM placement, and static VM placement:

1.3 Research Goals

The overall goal of this thesis is to propose an end-to-end server consolidation approach that considers all three stages in the resource management as well as the large scale problem. More, specifically, this approach combines element of AI planning, to ensure the objectives and constraint fulfilment, and of Evolutionary Computation, to evolve a population of near-optimal solutions. The research aims to determine a flexible way in which planning and EC can be combined to allow the creation of solutions to solve server consolidation problems. The research goal described above can be archieved by completing the following set of objectives.

1. In a CaaS cloud model, the initial VM provisioning and placement become a joint allocation of containers and virtual machines. This joint allocation is one of the major improvement in energy efficiency in CaaS which will be detailed explain in the next section. The joint allocation can be separated into two steps, in the first step, the tasks are mapped to VMs and the VMs are allocated to physical machines in the second step. Because of the complexity, previous research only considers the first step. They map the incoming tasks into predefined categories and based on the characteristic of the categories, the size of new virtual machines' resources are decided. After each tasks have chosen its VM type, they are allocated to virtual machines using a lightweight heursitic algorithm. We intend to apply an EC-based approach to solve this problem by proposing a coevolutionary that simuetiously decide the virtual machine type as well as the allocation of VMs.

2. Dynamic server consolidation is the process that the resource management continuously detects the server runtime status and if one of the server is overloaded. Then, one of the VM or container running inside the server will be migrated to other machine so that the applications do not suffer from a performance degradation. In a container-based environment, there are three questions to be answered. *When to migrate ?* refers to determine the time point that a physical server is overloaded. *Which container to migrate?* refers to determine which container need to be migrated so that it optimize the global energy consumption. *Where to migrate?* refers to determine which VM and host that a container is migrated to. Specifically, in the second question, the main idea in the literature is still simple heuristics and random selection. Therefore, we are going to investigate using a genetic programming technique to learn to choose the best. In the third question, literature also rely on simple bin-packing heuristics which do not consider the impact of environment. Therefore, we are going to propose an idea which uses the features of workload, to decide which VM is the best choice.

3. Static server consolidation is the process that a batch of VM and container joint is consolidated in order to achieve an low energy consumption status. This stage is often applied when the overall energy consumption is reached a predefine threshold. The static server consolidation can globally optimize the energy consumption of the data center. The process is similar with the initialization stage but with different objectives and constraints.

4. Large scale of server consolidation has always been a challenge in a Cloud data center. Especially, typical number of servers in a data center is at the million-level. Many approaches have been proposed in the literature to resolve the problem. There are mainly

two ways, both rely on distributed methods, hierarchical-based [] and agent-based management systems []. The major problem in agent-based systems is that agents rely on heavy communication to maintain a high-level utilization. Therefore, it causes heavy load in the networking. Hierarchical-based approaches are the predominate methods. Hierarchical-based methods, in essence, are centralized systems where all the states of machines are collected and analyzed. One of way to improving the effectiveness of centralized system is to reduce the number of variables so that the search space is narrowed. In this thesis, we are going to investigate the way to eliminate the redundant information.

1.4 Published Papers

During the initial stage of this research, some investigation was carried out on the model of container-based server consolidation.

1. Tan, B., Ma, H., Mei, Y. and Zhang, M., "A NSGA-II-based Approach for Web Service Resource Allocation On Cloud". *Proceedings of 2017 IEEE Congress on Evolutioanry Computation (CEC2017).* Donostia, Spain. 5-8 June, 2017.pp.

Chapter 2

Literature Review

Background

An Overview of Resource Allocation in Cloud

The reasons for energy wastage can be derived from several components of a data center, including cooling systems, network equipments, and server consumption. A recent survey [4] shows that the recent development of cooling techniques have reduced its energy consumption and now server consumption has become the dominate energy consumption component. Despite improvements in hardwares, various software techniques have been proposed to reduce the energy consumption of servers such as: Server Consolidation and Dynamic Voltage and Frequency Scaling (DVFS) [].

Server consolidation [21] is one of the widely used strategies for resource management [13]. It reduces the server energy consumption by gathering virtual machines (VMs) into a fewer number of physical servers so that idle servers can be turned off. The server consolidation techniques on the server-level have been extensively studied in the past decade []. However, the recent development of container technology enables a VM-level of consolidation, which has not driven much attention. Container is a lightweight virtualization technology which allows an application running in a single container. Multiple containers can be packed in a single virtual machine. Two main advantages make the container popular. First, containers do not need a Virtual Machine Monitor (VMM) but relies on the operating system; it reduces the overhead used on managing the virtual system. Second, the communication [] between containers are much easier (e.g. inter-process communication) than an inter-VM communication. This feature is particularly useful for micro-service-based Web applications where their processes are packed into separated containers. This new technology has brought new challenges to server consolidation. Traditional algorithms can not be directly applied since there is an extra level of virtualization. Affinity and communication aware allocation play an much important role in container-based environment. Therefore, new techniques and algorithms are need to be proposed.

Server consolidation is often considered as a global optimization problem where its goal is to minimize the energy consumption. Challenges are posed at different stages of consolidation process. Static problem is often modeled as a bin-packing problem [11] which is known as NP-hard meaning it is unlikely to find an optimal solution of a large problem. Furthermore, server consolidation often has much complicated assumptions and constraints - including multi-dimension resources, migration cost, and heterogeneous bins [11]. Because of its NP-hard nature, deterministic methods such as Integer Linear Programming [**?**] and Mixed Integer Programming [] are unsuitable for a large scale problem because of the long computation time. Heuristic methods such as First Fit Decreasing (FFD) [14], Best Fit Decreasing (BFD) [20], and other bin packing algorithms are often applied to approximate the optimal solution. As [11] shown, server consolidation is a lot more harder than bin-packing problem, therefore, these greedy-based heuristics can not reach a good approximation but easy to be stuck at a local optima.

This thesis, therefore, aims at providing an end-to-end solution to the container-based server consolidation problem.

Resource allocation and scheduling is the core of resource management in Cloud computing. The main purpose is to satisfy both Cloud users' and Cloud providers' requirements by allocating sufficient resources to incoming tasks as well as keep a high utilization of the resources. In order to accomplish this goal, resource allocation and scheduling tasks are often treated as optimization tasks.

An abstract model of resource allocation is shown in Figure **??**.

An Overview of Server Consolidation

A Service consolidation is the process of packing virtual machines in a number of physical machines in order to reach a high utilization of resource as well as using a minimum number of physical machines. The key aspect of server consolidation is that, in order to achieve the desired result, the permutation of virtual machines must be considered. It is important to list the difference between a static and dynamic server consolidation approaches []. Static In static approaches, . In dynamic approaches, bla.... A typical system model for a data center resource management system can be seen in Figure **??**.

A dynamic server consolidation approach can usually be decomposed into a series of steps, reflecting the process required to produce a solution []. These steps are shown in Figure **??** and discussed below:

1. When to migrate. Dynamic migration occurs on two scenarios: migrating VMs from overloaded server; and item migrating VMs from underloaded server.

2. Which VMs to migrate. After deciding to migrate a VM from a server, the next step is to make a decision of which VM to migrate.

3. Where to migrate the VMs. The key step is to determine where to allocate a VM which leads to global optimization.

A Comparison between CaaS and IaaS based Cloud model

From a computing system design point of view, we believe service allocation and VM Placement are closely related and should be considered as a single allocation task.

Service Allocation

Service allocation refers to the process of mapping a Web service on a certain type of VM. It is conducted by Cloud customers (e.g Web service providers) or Cloud brokers deligated by a Cloud customer. The resource mapping involve with two steps, resource demand profiling [] and VM selection []. Resource demand profiling is an estimation of the workload of a service. Because the web application has dynamic workload over time [], service providers or cloud brokers normally would like to estimate the future workload so that they can choose how much resources to rent in order to guarantee the Service Level Agreements (SLAs) [] to end customers. In this step, historical statistics are often used and based on its peak workload estimation, service providers often rent resources more than they need. Since the peak dataCenter-1.png

Figure 2.1: A datacenter management model [19]

workload only accounts for a small portion of its total operation time, intelligent strategies are applied to tackle the over-provisioning and under-provisioning problems.

Public Cloud providers often provide various configurations of VM, often refered to as VM types or instance types [10]. An instance type is defined as its resources such as memory size, number of processors and CPU frequency.

Previous research focus on how to rent an appropriate amount of resources so that it minimize the service providers' costs.

Ref [3] considers e-Science applications with bag-of-tasks (BoT) model. It aims at executing a bag of independent tasks with the least amount of Cloud resources before a deadline. Unlike a service allocation problem, where service is permanantly deployed in a reserved VM, they consider an on-demand VM allocation. That means, when a bag of tasks comes, the system dynamically assign a set of VM to execute these tasks. It evaluates four heuristic algorithms and concludes that a greedy-based approach achieves the best result.

Li et al [10] consider a dynamic cloud scheduling problem from Cloud brokers' perspective. It considers scenarios such as Cloud provider changing its offer (e.g changing of pricing schemes or VM types) and service performance changing, a cloud broker needs to adjust the VMs allocation across multiple Cloud providers. This work proposes a model which maximize a Cloud consumers' profit by adjusting VMs across multiple Clouds. Their model does not consider a Cloud provider's profit.

An Overview of Evolutionary Computation

Initial Placement

Container-based VM Multiplexing

Container has been introduced back in the 1980s' []. The recent development of container allows only one process running in a container; this is revolutionary invention is called application container. It plays an important role in Cloud computing since it is lightweighted, easier to configure and enable finer adjustment than the VM-based resource management.

container.png

Figure 2.2: A Container as a Service Deployment Model

Chapter 3

Preliminary Work

Chapter 4

Proposed Contributions and Project Plan

The contributions are...

Bibliography

[1] BARROSO, L. A., AND HÖLZLE, U. The Case for Energy-Proportional Computing. *IEEE Computer 40*, 12 (2007), 33–37.

[2] BUYYA, R., YEO, C. S., VENUGOPAL, S., BROBERG, J., AND BRANDIC, I. Cloud computing and emerging IT platforms: Vision, hype, and reality for delivering computing as the 5th utility. *Future Generation Computer Systems 25*, 6 (June 2009), 599–616.

[3] CANDEIA, D., SANTOS, R. A., LOPES, R. V., AND BRASILEIRO, F. V. Investigating Business-Driven Cloudburst Schedulers for E-Science Bag-of-Tasks Applications. *CloudCom* (2010).

[4] CHO, J., AND KIM, Y. Improving energy efficiency of dedicated cooling system and its contribution towards meeting an energy-optimized data center. *Applied Energy 165* (Mar. 2016), 967–982.

[5] GUPTA, R., BOSE, S. K., SUNDARRAJAN, S., CHEBIYAM, M., AND CHAKRABARTI, A. A Two Stage Heuristic Algorithm for Solving the Server Consolidation Problem with Item-Item and Bin-Item Incompatibility Constraints. *IEEE SCC* (2008).

[6] HAMEED, A., KHOSHKBARFOROUSHHA, A., RANJAN, R., JAYARAMAN, P. P., KOLODZIEJ, J., BALAJI, P., ZEADALLY, S., MALLUHI, Q. M., TZIRITAS, N., VISHNU, A., KHAN, S. U., AND ZOMAYA, A. Y. A survey and taxonomy on energy efficient resource allocation techniques for cloud computing systems. *Computing 98*, 7 (2016), 751–774.

[7] JUNG, G., JOSHI, K. R., HILTUNEN, M. A., SCHLICHTING, R. D., AND PU, C. Generating Adaptation Policies for Multi-tier Applications in Consolidated Server Environments. *ICAC* (2008).

[8] KAPLAN, J. M., FORREST, W., AND KINDLER, N. Revolutionizing data center energy efficiency, 2008.

[9] LI, B., AND JIANXIN, L. *An Energy-saving Application Live Placement Approach for Cloud Computing Environment*. ACM International Conference on Cloud Computing, 2009.

[10] LI, W., TORDSSON, J., AND ELMROTH, E. Modeling for Dynamic Cloud Scheduling Via Migration of Virtual Machines. *CloudCom* (2011).

[11] MANN, Z. Á. Approximability of virtual machine allocation: much harder than bin packing.

[12] MANN, Z. Á. Interplay of Virtual Machine Selection and Virtual Machine Placement. In *Service-Oriented and Cloud Computing*. Springer International Publishing, Cham, Aug. 2016, pp. 137–151.

[13] Marinescu, D. C. *Cloud computing: theory and practice*. Newnes, 2013.

[14] Panigrahy, R., Talwar, K., Uyeda, L., and Wieder, U. Heuristics for vector bin packing. *research microsoft com* (2011).

[15] Rong, H., Zhang, H., Xiao, S., Li, C., and Hu, C. Optimizing energy consumption for data centers. *Renewable and Sustainable Energy Reviews 58* (May 2016), 674–691.

[16] Speitkamp, B., and Bichler, M. A mathematical programming approach for server consolidation problems in virtualized data centers. *IEEE Transactions on services ...* (2010).

[17] Tomás, L., and Tordsson, J. Improving cloud infrastructure utilization through overbooking. *CAC* (2013), 1.

[18] Uhlig, R., Neiger, G., Rodgers, D., Santoni, A. L., Martins, F. C. M., Anderson, A. V., Bennett, S. M., Kägi, A., Leung, F. H., and Smith, L. Intel Virtualization Technology. *IEEE Computer 38*, 5 (2005), 48–56.

[19] Varasteh, A., and Goudarzi, M. Server Consolidation Techniques in Virtualized Data Centers: A Survey. *IEEE Systems Journal* (2015), 1–12.

[20] Xu, J., and Fortes, J. A. B. Multi-Objective Virtual Machine Placement in Virtualized Data Center Environments. *GreenCom/CPSCom* (2010).

[21] Zhang, Q., Cheng, L., and Boutaba, R. Cloud computing: state-of-the-art and research challenges. *Journal of internet services and ...* (2010).