

Chapter 1

Introduction

1.1 Problem Statement

Cloud computing definition

Cloud computing is a computing model offers a network of servers to their clients in a on-demand fashion. From NIST's definition [23], *"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 advantages from clients' perspective

Cloud computing has completely reformed the software industry [6] 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.

Research Problem from Cloud Providers' Perspective

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 attract more service providers. On the other hand, they want to cut enormous energy consumption - as much as 25,000 households [19] - to lower the expense.

Energy consumption in data centers are derived from several parts as illustrated in Figure 1.2. Regardless the energy consumption of refrigeration system (or cooling system), the majority. According to Hameed et al [13], servers are far from energy-efficient and the main reason for the wastage is "the idle power when ICT resources such as servers run at low

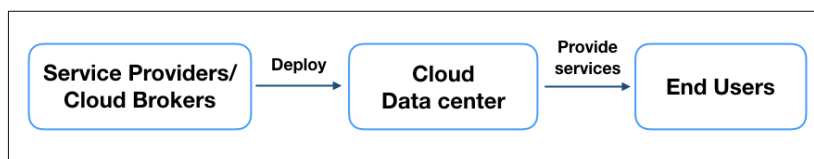


Figure 1.1: Stakeholders of Cloud computing

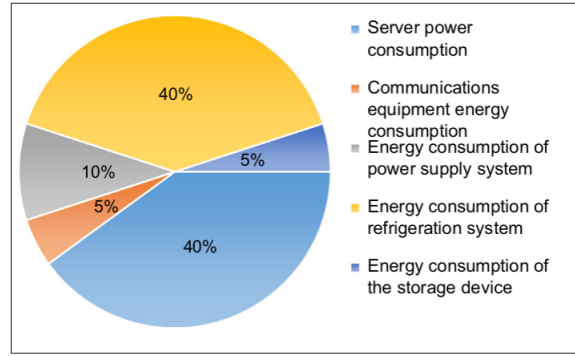


Figure 1.2: Energy consumption distribution of data centers [28]

utilization". Therefore, a concept of *energy proportional computing* [3] raised to address the low utilization and it leads to the virtualization technology and server consolidation.

Virtualization [35] partitions a physical machine's resources (e.g. CPU, memory and disk) into several isolated units called virtual machines (VMs) where each VM allows an operating system running on them. This technology rooted back in the 1960s' and was originally 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 [41] resolves the low utilization problem by gathering virtual machines (VMs) into a fewer number of physical machines (PMs), so that the resource utilization of PMs are maintained at a high level. In the meanwhile, idle servers are turned off to save energy.

Difficulties

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 [21]. 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 [33] and Mixed Integer Programming [36] 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) [25], Best Fit Decreasing (BFD) [38]. In addition, manually designed heuristics are designed to tackle the special requirements such as a bin-item incomplete scenario [12] and Multi-tier Applications [18, 20]. Although these greedy-based heuristics can quickly solve the consolidation problem, as Mann's research [21] 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.

New technology

In addition, virtualization technology has evolved to allow finer granularity resource scheduling. A recent development of Container technique [31] has drew the attention of both industrial and academia. Container is an operating system level of virtualization which means multiple containers can be installed in a same operating system. Each container provides an isolated environment for an application. In short, a VM is partitioned into smaller manageable units. This new concept starts a new service model called Container as a Service

(CaaS) [27]. CaaS has advantages of both IaaS and PaaS but without their disadvantages. On one hand - similar to PaaS - it removes the customers' responsibility of estimation of resources. On the other hand - similar to IaaS - it allows customers' to customize their software environment. From Cloud providers' perspective, CaaS allows Cloud providers to manage both the deployment of applications and resource allocation. Hence, Cloud providers have a complete control of resources which may lead to a better utilization of resources. However the management difficulty also increases. Currently, vast amount of research focus on VM-based server consolidation, which can not be directly used on Contained-based model. This thesis, therefore, aims at providing an end-to-end solution which includes three stages: initialization, static container-based server consolidation and dynamic container placement.

1.2 Motivation

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

1.2.1 Motivation For Container-based Server Consolidation Problem

1. Container is a new virtualization technology which provides an operating level of virtualization. Figure 1.3 illustrates the root of container technology from an energy efficient 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 resources [8].
 - Secondly, specific types of application may use a type of resources a lot more than another [34], for example, computation intensive tasks consume CPU much more than RAM; a fixed type of VM may provide 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 workload prediction on the application 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.

Despite the potential improvement in energy efficiency, containers have advantages on other aspects. In terms of resource utilization, traditional IaaS (Infrastructure as a Service) Cloud data centers run many redundant operating systems and hypervisors. These redundancies can be eliminated by running multiple containers in a same operating system. From service model's perspective, softwares running in PaaS (Platform as a Service) must be compatible with the platform: all technologies including programming languages, libraries must be supported by the platform. CaaS enhances PaaS by providing separated software runtime environment. These advantages make the container technology a popular trend. This is the reason that attracts us to do research in this field.

2. This container technology certainly brings many advantages to current Cloud industry[10]. However, it also brings difficulties for server consolidation. Server consolidation prob-

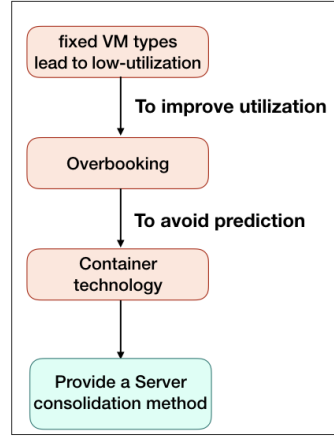


Figure 1.3: The root of container technology

lems are typically modeled as vector bin-packing problem which are NP-hard. Container-based server consolidation adds 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 interact with each other. Piraghaj [26] proposes a two-step procedure; it first maps tasks to VMs and then allocate containers to VMs. As Mann illustrated in [22], these two steps should be conducted simultaneously, otherwise it leads to local optimal. Other research [9, 14, 1] propose greedy-based heuristics on container allocation problem. They are fast in execution, but they can be easily stuck at local optimal. Therefore, it motivates us to provide *global optimized* resource allocation solution for container-based data centers.

1.2.2 Motivation For Research Objectives

The container-based consolidation problem, similar to VM-based consolidation, can be seen as a continuous optimization procedure with several stages. The goals for different stages are distinct, therefore, they can be seen as separate research questions. In this thesis, we aims at providing an end-to-end solution to the problem. Therefore, we divide the procedure into three stages: initialization, offline static optimization and online dynamic optimization stage. In addition to these three research questions, a scalability problem of static optimization is also considered as an objective.

1. In a CaaS cloud model, the initialization stage can be seen as a joint allocation of containers and virtual machines. This joint allocation is key step in ensuring energy efficiency. At the initial stage, a set of containers is allocated to empty VMs and these VMs are allocated to physical servers. This seemingly two-step procedure is interconnected, therefore, should be conducted simultaneously. Because previous research [16] focus on VM-based optimization, new problem models, including price and power model, constraints, and optimization objectives, are the primary issue. In the second step, we will consider different representations and algorithms for solving this problem.
2. Server consolidation can be considered as static or dynamic problem [37]. Cloud data center has a highly dynamic nature with arrival and release of VMs. Therefore, after the initial allocation, the energy efficiency keeps dropping. At a certain time point, e.g. a fixed time interval, a *static server consolidation* is conducted to improve the global

energy efficiency. Similar with VM-based consolidation, the problem is considered as a multi-objective problem with minimization of migration cost as well as keeping a good energy efficiency. Distinct from previous studies, the problem model has become a two-level of bin-packing problem which both container and VM migration cost should be considered.

3. Dynamic consolidation is another method to maintain a high energy efficiency. Unlike static consolidation is conducted periodically in a global scale, dynamic consolidation is applied on single VM or container at any time point. At large, data center system monitors all the states of servers for overloaded and underloaded servers. Once an overloaded server is detected, 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; for an underloaded server, all its applications will be moved to other servers so that it can be turned off. In conclusion, the main goal for dynamic consolidation is to optimize the global energy consumption as well as prevent overloading. In a container-based environment, it involves three steps .
 - *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, we focus on the third question: dynamic placement problem. Previous research employ simple heuristics [30, 11, 4], they are fast but could not perform well. Multi-objective genetic algorithm (GA) [38] has been applied. However, GA is too slow for dynamic problem.

To solve a dynamic placement with large number of variables, heuristics and dispatching rules are often used[29]. In this scenario, a dispatching rule is considered as a function that determines the priorities of servers that a container can be placed. However, dynamic placement is much complex than bin-packing problem [21]. Therefore, we intend to develop a hyper-heuristic method - Genetic Programming (GP) technique [2] or artificial immune system [15]- to automatic evolve dispatching rules to solve this problem. GP has been applied in generating dispatching rules for bin-packing problem [5, 32] and it produces promising solutions.

4. Cloud data center typically has hundreds of thousands servers and more. Large scale of server consolidation has always been a challenge. Many approaches have been proposed in the literature to resolve the problem. There are mainly two ways, both rely on distributed methods, hierarchical-based [17, 24] and agent-based management systems [39]. 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. In essence, these approaches are static methods where all the states of machines are collected and analyzed. In fact, it is infeasible and unnecessary to check all the states of machines since the search space is too large and most machines do not need a change. This idea motivates a way to improving the effectiveness 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.

1.3 Research Goals

The overall goal of this thesis is to propose an end-to-end server consolidation approach that considers all three stages: Initialization, Off-line Static Joint Allocation of Container and VM, On-line Dynamic Container Placement Problem. In addition, the static allocation normally involves with large amount of variables which is particular difficult to optimize. We also going to propose a method to solve this problem. These approaches combine element of AI planning, to ensure the objectives and constraint fulfillment, 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. As discussed in the previous section, the research goal can be achieved in the following objectives and sub-objectives.

1. The initialization Problem,

Currently, most research focus on VM-based server consolidation technique. They often modeled this problem as a vector bin-packing problem [40]. Container adds an extra layer of abstraction on top of VM. The placement problem has become a two-step procedure, in the first step, containers are packed into VMs and then VMs are consolidated into physical machines. These two steps are inter-related to each other.

- (a) *Modeling*

Previous VM-based models do not consider this structure, therefore, our first sub problem is to propose a description of model for the initialization problem. In order to achieve this goal, we will first review the related models including VM-based placement model and bilevel optimization model. Furthermore, we are going to consider the differences and design the constraints and other characteristics.

- (b) *Representation*

Based on this new model, we are going to discover a representation that suitable for this problem.

- (c) *New operators and searching mechanisms*

In order to utilize Evolutionary Computation (EC) to solve this problem, we are going to design searching mechanisms according to the nature of problem. In order to achieve this goal, we will design several new operators.

2. Off-line Static Joint Allocation of Container and VM Problem,

A static allocation can be seen as a resource scheduling problem. A schedule is robust if it is able to absorb some degree of uncertainty in tasks duration while maintaining a stable solution [7]. Cloud resource management is a continuous process, after each static allocation, the system should be able to maintain a stable status with the least adjustment. The development of static allocation approach has three sub-objectives.

- (a) *Design a robustness measure*

Previous studies only use simple measurement which counts the migration number between two static consolidation. This measurement aims at minimizing the number of migration in a static placement process. It may cause more migration in the next consolidation. Therefore, it needs a time-series aware measure of the robustness of system. A data center should be both consolidated as well as robustness after consolidate. Therefore, in this objective, the first sub-problem we are going to solve is to propose a robustness measure.

- (b) *Design an allocation method consider previous allocation*

Based on the robustness measure, we will first design an allocation method which takes previous allocation into account. It has two objectives, maximize the robustness and also minimize the energy consolidation.

- (c) *Design a time-series-aware allocation method*

Last but not the least, we will generalize the previous sub-objective to a more general one: design a time-series-aware allocation method which takes several allocation into consider.

3. On-line Dynamic Container Placement Problem with a GP approach,

- (a) Representation

In order to utilize a hyper-heuristic method such as GP to solve the problem, the first step is to design a representation.

- (b) Construct Functional Set and Primitive Set for the problem

As the basic component of a dispatching rule, primitive set contains the states of environment including: status of VMs, features of workloads. The functional set contains the operators which combines low level features.

- (c) Develop GP-based methods for evolving Dispatching rules

- (d) One heuristic can solve all the problem or different heuristics to solve specific problems.

4. Large-scale Static Consolidation Problem

- (a) Propose a preprocessing method to eliminate variables

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 Evolutionary Computation (CEC2017)*. Donostia, Spain. 5-8 June, 2017.pp.

1.5 Organisation of Proposal

The remainder of the proposal is organised as follows: Chapter ?? provides a fundamental definition of the Container-based server consolidation problem and performs a literature review covering a range of works in this field; Chapter ?? discusses the preliminary work carried out to explore the techniques and EC-based techniques for the initialization problem; Chapter ?? presents a plan detailing this projects intended contributions, a project timeline, and a thesis outline.

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