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 [21], *"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 [5] 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 [17] - 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 [11], 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* [3] raised to address the low utilization and it leads to the vitualization technology and server consolidation.

Virtualization [32] 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 [37] resolves the low utilization problem by gathering virtual machines (VMs) into a fewer number of physical machines (PMs), so that the resource utiliza-

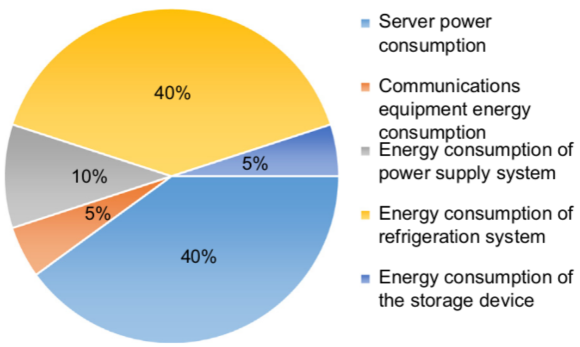

Figure 1.1: Energy consumption distribution of data centers [26]

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 [19]. 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 [30] and Mixed Integer Programming [33] 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) [23], Best Fit Decreasing (BFD) [35]. In addition, manually designed heuristics are designed to tackle the special requirements such as [18, 10, 16]. Although these greedy-based heuristics can quickly solve the consolidation problem, As Mann's research [19] 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 [29] 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) [25] 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 focus on VM-based server consolidaton 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 the roots of container-based server consolidation problem. In the second parts, we explain the motivations for solving the sub-problems of the problem.

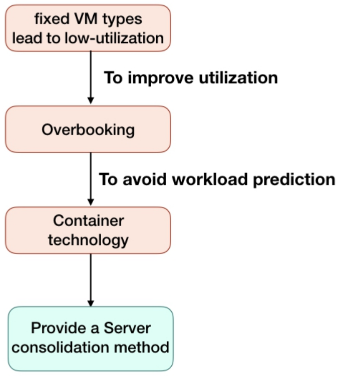

Figure 1.2: The root of container technology

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 1.2 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 [6].
   - Secondly, specific types of application may use a type of resources a lot more than another [31], 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[8]. 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 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 [24] proposes a two-step procedure; it first maps tasks to VMs and then allocate containers to VMs. As Mann illustrated in [20], these two steps should be conducted simultaneously, otherwise it leads to local optimal. Other research [7, 12, 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 [14] 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 [34]. 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 [28, 9, 4], they are fast but could not perform well. Multi-objective genetic algorithm (GA) [35] has been applied. However, GA is too slow for dynamic problem.

To solve a dynamic placement with large number of variables, dispatching rule can be an useful tool [27]. In this scenario, a dispatching rule is considered as a function that determines the priorities of servers that a container can be placed. We intend to develop a hyper-heuristic method - genetic programming (GA) technique [2] or artificial immune system [13]- to automatic evolve dispatching rules to solve this problem.

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 [15, 22] and agent-based management systems [36]. 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. One of 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 in the resource management as well as the large scale static optimization 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. As discussed in the previous section, the research goal can be achieved in the following objectives and sub-objectives.

1. The initialization Problem,
   - Problem Model
   - Representation
   - Algorithm
   - Evaluation and Comparison
2. Offline Static Joint Allocation of Container and VM Problem,
   - Problem Model
   - Representation
   - Algorithm
   - Evaluation and Comparison

3. Online Dynamic Container Placement Problem with a GP approach,
    - Problem Model
    - Representation
    - Construct Functional Set and Primitive Set for the problem
    - Develop a GP-based method for evolving Dispatching rules
    - Evaluation and Comparison
4. Large-scale Static Consolidation Problem
    - Propose a preprocessing method to eliminate variables
    - Apply static consolidation algorithm on the processed dataset
    - Evaluation and Comparison

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.

Bibliography

[1] ANSELMI, J., AMALDI, E., AND CREMONESI, P. Service Consolidation with End-to-End Response Time Constraints. *EUROMICRO-SEAA* (2008), 345–352.

[2] BANZHAF, W., NORDIN, P., KELLER, R. E., AND FRANCONE, F. D. Genetic programming: an introduction, 1998.

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

[4] BELOGLAZOV, A., ABAWAJY, J. H., AND BUYYA, R. Energy-aware resource allocation heuristics for efficient management of data centers for Cloud computing. *Future Generation Comp. Syst. 28*, 5 (2012), 755–768.

[5] 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.

[6] CHAISIRI, S., LEE, B.-S., AND NIYATO, D. Optimization of Resource Provisioning Cost in Cloud Computing. *IEEE Trans. Services Computing 5*, 2 (2012), 164–177.

[7] DONG, Z., ZHUANG, W., AND ROJAS-CESSA, R. Energy-aware scheduling schemes for cloud data centers on Google trace data. *OnlineGreenComm* (2014), 1–6.

[8] FELTER, W., FERREIRA, A., RAJAMONY, R., AND RUBIO, J. An updated performance comparison of virtual machines and Linux containers. *ISPASS* (2015), 171–172.

[9] FORSMAN, M., GLAD, A., LUNDBERG, L., AND ILIE, D. Algorithms for automated live migration of virtual machines. *Journal of Systems and Software 101* (2015), 110–126.

[10] 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).

[11] 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.

[12] HINDMAN, B., KONWINSKI, A., ZAHARIA, M., GHODSI, A., JOSEPH, A. D., KATZ, R. H., SHENKER, S., AND STOICA, I. Mesos - A Platform for Fine-Grained Resource Sharing in the Data Center. *NSDI* (2011).

[13] HOFMEYR, S. A., AND FORREST, S. Architecture for an Artificial Immune System. *Evolutionary Computation 8*, 4 (2000), 443–473.

[14] JENNINGS, B., AND STADLER, R. Resource Management in Clouds: Survey and Research Challenges. *Journal of Network and Systems Management 23*, 3 (2015), 567–619.

[15] JUNG, G., HILTUNEN, M. A., JOSHI, K. R., SCHLICHTING, R. D., AND PU, C. Mistral - Dynamically Managing Power, Performance, and Adaptation Cost in Cloud Infrastructures. *ICDCS* (2010), 62–73.

[16] 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).

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

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

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

[20] 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.

[21] MELL, P. M., AND GRANCE, T. The NIST definition of cloud computing. Tech. rep., National Institute of Standards and Technology, Gaithersburg, MD, Gaithersburg, MD, 2011.

[22] MOENS, H., FAMAEY, J., LATRÉ, S., DHOEDT, B., AND DE TURCK, F. Design and evaluation of a hierarchical application placement algorithm in large scale clouds. *Integrated Network Management* (2011), 137–144.

[23] PANIGRAHY, R., TALWAR, K., UYEDA, L., AND WIEDER, U. Heuristics for vector bin packing. *research microsoft com* (2011).

[24] PIRAGHAJ, S. F., CALHEIROS, R. N., CHAN, J., DASTJERDI, A. V., AND BUYYA, R. Virtual Machine Customization and Task Mapping Architecture for Efficient Allocation of Cloud Data Center Resources. *Comput. J. 59*, 2 (2016), 208–224.

[25] PIRAGHAJ, S. F., DASTJERDI, A. V., CALHEIROS, R. N., AND BUYYA, R. Efficient Virtual Machine Sizing for Hosting Containers as a Service (SERVICES 2015). *SERVICES* (2015).

[26] 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.

[27] SARIN, S. C., VARADARAJAN, A., AND WANG, L. A survey of dispatching rules for operational control in wafer fabrication. *Production Planning and ... 22*, 1 (Jan. 2011), 4–24.

[28] SHI, W., AND HONG, B. Towards Profitable Virtual Machine Placement in the Data Center. *UCC* (2011), 138–145.

[29] SOLTESZ, S., PÖTZL, H., FIUCZYNSKI, M. E., BAVIER, A. C., AND PETERSON, L. L. Container-based operating system virtualization - a scalable, high-performance alternative to hypervisors. *EuroSys 41*, 3 (2007), 275–287.

[30] SPEITKAMP, B., AND BICHLER, M. A mathematical programming approach for server consolidation problems in virtualized data centers. *IEEE Transactions on services ...* (2010).

[31] TOMÁS, L., AND TORDSSON, J. Improving cloud infrastructure utilization through overbooking. *CAC* (2013), 1.

[32] 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.

[33] WANG, Y., AND XIA, Y. Energy Optimal VM Placement in the Cloud. In *2016 IEEE 9th International Conference on Cloud Computing (CLOUD* (2016), IEEE, pp. 84–91.

[34] XIAO, Z., JIANG, J., ZHU, Y., MING, Z., ZHONG, S.-H., AND CAI, S.-B. A solution of dynamic VMs placement problem for energy consumption optimization based on evolutionary game theory. *Journal of Systems and Software 101* (2015), 260–272.

[35] XU, J., AND FORTES, J. A. B. Multi-Objective Virtual Machine Placement in Virtualized Data Center Environments. *GreenCom/CPSCom* (2010).

[36] YAZIR, Y. O., MATTHEWS, C., FARAHBOD, R., NEVILLE, S. W., GUITOUNI, A., GANTI, S., AND COADY, Y. Dynamic Resource Allocation in Computing Clouds Using Distributed Multiple Criteria Decision Analysis. *IEEE CLOUD* (2010), 91–98.

[37] ZHANG, Q., CHENG, L., AND BOUTABA, R. Cloud computing: state-of-the-art and research challenges. *Journal of Internet Services and Applications 1*, 1 (2010), 7–18.