Jyoti al. International Journal of Recent Research Aspects ISSN: 2349-7688, Vol. 4, Issue 1, March 2017, pp. 132-137

A Systematic Study of Distributed Virtual Machine

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Abstract: **Background: Virtual Machine (VM) consolidation is an effective technique to improve resource utilization and reduce energy footprint in cloud data centers. It can be implemented in a centralized or a distributed fashion. Distributed VM consolidation approaches are currently gaining popularity because they are often more scalable than their centralized counterparts and they avoid a single point of failure. Objective: To present a comprehensive, unbiased overview of the state-of-the-art on distributed VM consolidation approaches. Method: A Systematic Mapping Study (SMS) of the existing distributed VM consolidation approaches. Results: 19 papers on distributed VM consolidation categorized in a variety of ways. The results show that the existing distributed VM consolidation approaches use four types of algorithms, optimize a number of different objectives, and are often evaluated with experiments involving simulations. Conclusion: There is currently an increasing amount of interest on developing and evaluating novel distributed VM consolidation approaches. A number of research gaps exist where the focus of future research may be directed.**

Keywords: **Cloud computing, Data center, Virtual machine ,Consolidation Placement, Energy-efficiency**

I. INTRODUCTION

Energy footprint of cloud data centers is a matter of great concern for cloud providers [1]. According to a recent report [2], data centers in the United States consumed an estimated 70 bil- lion kilowatt-hours of electricity in 2014, which corresponds to 1.8% of total United States electricity consumption. High energy consumption not only translates into a high operating cost, but also leads to huge carbon emissions. The ever increasing demand for computing resources to provide highly scalable and reliable services has caused an energy crisis [3]. The high energy con- sumption of data centers can partly be attributed to the large- scale installations of computing and cooling infrastructures, but more importantly it is due to the inefficient use of the computing resources [4]. Production servers seldom operate near their full capacity [5]. However, even at the completely idle state, they con- sume a substantial proportion of their peak power [6]. Therefore, under-utilized servers are highly inefficient.

Hardware virtualization technologies allow to share a Physical Machine (PM) among multiple, performance-isolated platforms called Virtual Machines (VMs) to improve resource utilization. Fur- ther improvement in resource utilization and reduction in energy consumption can be achieved by consolidating VMs on under- utilized PMs. The basic idea of VM consolidation is to migrate and place the VMs on as few PMs as possible and then release the remaining, unused PMs for termination or for switching to a low- power mode to conserve energy. A VM consolidation approach uses live VM migration to consolidate VMs on a reduced set of PMs. VM consolidation has emerged as one of the most effective and promising techniques to reduce energy footprint of cloud data centers [4,7].

Fig. 1 presents a simple hypothetical scenario to illustrate the VM consolidation process. The first half of Fig. 1 shows three PMs where each PM hosts multiple VMs and every VM uses a certain amount of the PM resources. It is assumed that due to some signif- icant load variations, PM 2 and PM 3 have become under-utilized. The under-utilized PMs in such a scenario may continue to remain under-utilized for hours, days, or even weeks unless the existing VMs require more resources or some new VMs are placed on the under-utilized PMs. Therefore, it is difficult to provide a resource and energy efficient allocation of VMs without consolidation of VMs on the under-utilized PMs. The second half of Fig. 1 shows that after migrating all VMs from PM 2 to PM 3, PM 2 can be turned-off or switched to a low-power mode.

There is currently an increasing amount of interest on devel- oping and evaluating efficient VM consolidation approaches for cloud data centers. Over the past few years, researchers have used a multitude of ways to develop novel VM consolidation approaches. Some of these approaches have been recently reported in the form of nonsystematic literature reviews such as [8] and [9]. However, the drawback of these existing nonsystematic studies is that they provide a partial and possibly biased overview of the state-of- the-art on VM consolidation. For a comprehensive and unbiased coverage of the existing literature on VM consolidation, there is a need to study the existing VM consolidation approaches in a systematic way.

VM consolidation can be implemented in a centralized or a distributed fashion. Traditional VM consolidation approaches, such as [4,10–15], tend to be centralized. A centralized VM consolidation approach uses a centralized algorithm on a centralized architec- ture and does not provide support for multiple, geographically distributed data centers. The main drawbacks of centralized VM consolidation approaches include limited scalability and lack of robustness due to a single point of failure. On the other hand, a distributed or decentralized VM consolidation approach uses a distributed algorithm or a distributed architecture for PMs [7,16] or provides support for multiple, geographically distributed data centers [17,18]. Distributed VM consolidation is a recurring theme in recent VM consolidation approaches such as [7,19,16]. Dis- tributed approaches are gaining popularity because they have ben- efits over centralized approaches. They are often more scalable than their centralized counterparts and they avoid a single point of failure [19,20]. Feller et al. [16] showed that their proposed VM consolidation algorithm does not compute a solution.

II. RESEARCH QUESTIONS

The Research Questions (RQs) are as follows:

- RQ1: What approaches have been developed for distributed VM consolidation?
- RQ2: What kinds of algorithms are being used in the existing distributed VM consolidation approaches?
- RQ3: What objectives are being optimized in the existing distributed VM consolidation approaches?
- RQ4: How are the existing distributed VM consolidation approaches being evaluated?
- RQ5: What are the most popular publication forums for distributed VM consolidation papers and how have they changed over time?

RQ1 is the basic question for obtaining an overview of the state-of-the-art on distributed VM consolidation. RQ2 is aimed at obtaining the types of algorithms which are being used in the ex- isting distributed VM consolidation approaches. Possible types in- clude heuristics, metaheuristics, and machine learning algorithms. Moreover, the algorithms may also be categorized into offline and online optimization algorithms.

RQ3 concerns the objectives which are being optimized. Possi- ble objectives include minimizing energy consumption, minimiz- ing the number of active PMs, minimizing Service Level Agreement (SLA) violations, minimizing the number of VM migrations, mini- mizing cost, minimizing network traffic, maximizing performance, maximizing reliability, and minimizing resource utilization. RQ3 also deals with the number of objectives which are being optimized and how the optimization problem is formulated. Possible prob- lem formulations include single-objective, multi-objective (two or three objectives) with an Aggregate Objective Function (AOF), pure multi-objective, and many-objective (four or more objectives) [27]. RQ4 concerns the evaluation method. The most common eval- uation method in the VM consolidation literature is experiment. An experiment may involve the use of prototype implementations or simulations. Moreover, the experiment design may involve real- istic, synthetic, or hybrid load patterns. Similarly, an experimental evaluation may or may not include a comparison of the results with other existing VM consolidation approaches. Finally, a comparison of the results may or may not include statistical tests to assess the statistical significance of the results.

RQ5 is a typical question for SMSs in software engineering [23]. The objective is to identify the most popular, peer-reviewed publication forums with respect to distributed VM consolidation papers. The publication forums may include journals, conferences, and workshops. In addition, the second part of RQ5 concerns the frequencies of published papers in popular forums over time to see the trends.

Based on the RQs, the Population, Intervention, Comparison, Outcomes, and Context (PICOC) [28] is presented in Table 1.

Search strategy for primary studies

This section presents our search strategy. It is based on the SLR and SMS guidelines described by Kitchenham and Charters [28] and Wohlin et al. [26].

Search terms

Table 2 presents the most important search terms along with their alternate spellings. The search terms are primarily based on the RQs and PICOC in Section 2.1. Moreover, they are also in line with recent and prominent works on VM consolidation such as [4,7,10–12,19,13,14,16,15].

Search strings

The search strings are presented in Table 3. They are formed by making appropriate combinations of the search terms presented in Table 2. We used Boolean AND and Boolean OR operators to make the search strings. The two search strings in Table 3 can also be combined into one search string by using the Boolean OR operator. Therefore, the papers which contain any of the two search strings were retrieved. The search strings were validated against a set of known papers [7,19,16].

Databases

The search strings in Table 3 were searched in the publication title, abstract, and keywords. The following digital libraries were searched: (1) Institute of Electrical and Electronics Engineers (IEEE) Xplore, (2) Association for Computing Machinery (ACM) Digital Library, (3) ScienceDirect, and (4) SpringerLink. The search strings were customized for each digital library. Moreover, since using multiple digital libraries creates duplicates, the search results were analyzed to identify and remove the duplicates.

Search terms.

#	Search term	Alternate spellings
1	Consolidat*	Consolidate, consolidating, consolidation
2	Plac*	Place, placing, placement
3	Virtual machine*	Virtual machine, virtual machines
4	VM*	VM, VMs
5	Server*	Server, servers
6	Algorithm*	Algorithm, algorithms
7	Approach*	Approach, approaches
8	Method*	Method, methods
9	Heuristic*	Heuristic, heuristics
10	Cloud	None
11	Data center	Data center, datacenter, data centre, datacentre
12	Distributed	None
13	Decentralized	None

Table 3
Search strings.

#	Search string
1	(Distributed OR Decentralized) AND Consolidat* AND (‘‘virtual machine*’’ OR VM* OR server*) AND (algorithm* OR approach* OR method* OR heuristic*) AND (cloud OR ‘‘data center’’ OR datacenter OR ‘‘data centre’’ OR datacentre)

2	(Distributed OR Decentralized) AND Plac* AND (''virtual machine*'' OR VM*) AND (algorithm* OR approach* OR method* OR heuristic*) AND (cloud OR ''data center'' OR datacenter OR ''data centre'' OR datacentre)

Synthesis of the extracted data

The extracted data based on the data extraction strategy in Section 2.6 were synthesized separately for each RQ. The papers were categorized in a variety of dimensions and counts of the number of papers in different categories were recorded [26].

Perhaps the most important result of a SMS is a systematic map, which allows to identify evidence clusters and evidence deserts to direct the focus of future SLRs and to highlight areas where more primary studies should be performed [28]. It is important to present the systematic map in an appropriate visual format that provides a quick overview of the field and supports better analyses [23]. Therefore, a visual representation of the systematic map was created by using appropriate chart types including a pie chart and several bubble charts [25]. The visual representa- tion of the systematic map allowed thematic analysis [26] to see

III. SCHEDULE OF THE STUDY

initial search retrieved 202 results. However, out of 202, 86 were found duplicate and were subsequently removed. The main reason for such a large number of duplicate results is that the results from Which categories were well investigated and to identify research

Gaps [23]

Table 7 Number of papers in different stages.

SMS stage	Number of papers
Initial search results	202
After removing duplicates	116
After title and abstract level screening	41
After full-text level screening	21
After quality assessment	19

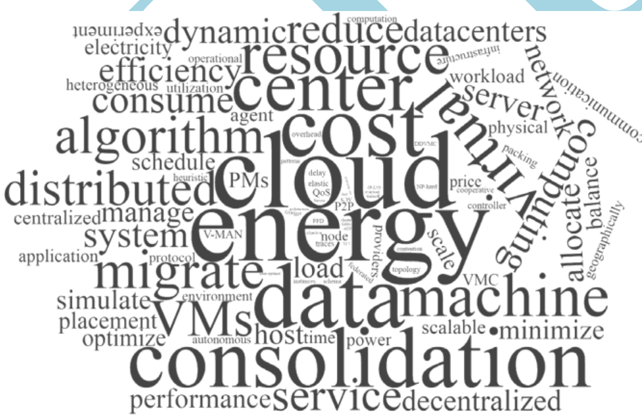

Fig. 2. Word cloud of the titles and abstracts of the 19 primary studies.

the ACM Digital Library were based on the ACM Guide to Comput- ing Literature, which provides an expanded search that includes papers from the ACM full-text collection as well as from a number of other digital libraries including IEEE Xplore, ScienceDirect, and SpringerLink. The advantage of using the ACM Guide to Computing Literature is that it often finds more papers,

The initial draft of the review protocol was written on 09.3.2016. From 10.3.2016 to 18.3.2016, the protocol went through internal and external reviews resulting in several major and minor revisions. The internal reviewers were the authors themselves, while the external reviewer was Muhammad Usman1 from the Department of Software Engineering at Blekinge Institute of Technology Table 6 presents the schedule of the SMS. The duration for title and abstract level screening was based on approximately 40 abstracts per day. Similarly, the duration for full-text level screening was based on approximately 5 full-text papers a day. The durations in Table 6 implicitly also include approximately 10% time for consensus meetings to resolve disagreements among the researchers. It should be noted that the search for primary studies was completed on 24.3.2016. Therefore, any papers published after this date are not covered in the mapping study.

IV. RESULTS

In this section, we present the results of the SMS on distributed VM consolidation approaches. Table 7 presents the number of papers in different stages of the SMS. The results show that the

but the disadvantage is that some of those papers are also found in the IEEE Xplore, ScienceDirect, and SpringerLink digital libraries. There were also a few cases where a VM consolidation approach was published in several papers. In such cases, only the most recent paper was included.

From the remaining 116 papers, 75 papers were removed in the title and abstract level screening, resulting in 41 papers. Another 20 papers were removed in the full-text level screening. Out of these, 15 did not present a VM consolidation approach [31–45], 2 presented a centralized VM consolidation approach [46,47], 2 were published in several papers [48,49], and 1 had a duplicate record [21]. Finally, from the remaining 21 papers, 2 papers were removed in the quality assessment stage because their aggregate scores were below the cutoff point [50,51]. It resulted in a total of 19 papers for data extraction and synthesis. Table 8 presents study identifiers (IDs) and references of the final selected primary studies. Each primary study in Table 8 presents a distributed VM consolidation approach.

Before presenting detailed results, we start with a simple, graphical overview of the topic. Fig. 2 presents a word cloud of distributed VM consolidation approaches generated from the titles and abstracts of the 19 primary studies. Common English words and those appearing only once were removed from the word list. Moreover, different forms and alternate spellings of a word were aggregated. The word cloud shows that some of the most frequent words include energy, cloud, data, and cost, which appear 56, 55, 46, and 45 times, respectively.

V. VALIDITY EVALUATION

In this section, we discuss major threats to the validity of the results presented in this paper. The first main threat is related to the coverage of the relevant literature. To mitigate this threat, we designed a comprehensive search strategy based on the SLR and SMS guidelines in [28,26]. The search terms were extracted from the RQs and were validated against a set of recent and prominent works on VM consolidation including [4,7,10–12,19,13,14,16,15].

Similarly, the search strings were validated against a set of known studies on distributed VM consolidation including [7,19,16]. The search was performed in four major computer science digital libraries. Finally, the search in the ACM Digital Library was performed by using the ACM Guide to Computing Literature, which provides an expanded search.

The second threat is related to the selection of the primary studies. The results show that 75 out of 116 papers were excluded in the title and abstract level screening. It is possible that some rele- vant papers were erroneously excluded during the initial screening phase. To mitigate this threat, two researchers (first and second author) independently screened the titles and abstracts of each paper. The results were compared and disagreements were resolved through discussions. Moreover, for any unresolved disagreements, consensus meetings [29] were arranged. A similar approach was used in the full-text level screening phase.

VI. CONCLUSIONS

In this paper, we presented a Systematic Mapping Study (SMS) of distributed Virtual Machine (VM) consolidation approaches. We used Systematic Literature Review (SLR) and SMS guidelines in the literature to design a comprehensive search strategy. The initial search returned 202 results from four major computer science digital libraries. After the removal of duplicate results and the application of the inclusion/exclusion criteria at two levels, 21 primary studies were selected. Finally, 2 studies were excluded in the quality assessment stage, which left 19 primary studies for data extraction and synthesis.

The objective of the SMS was to provide a comprehensive, unbiased overview of the state-of-the-art on distributed VM consolidation approaches. The SMS comprises five Research Questions (RQs) concerning: (1) existing approaches, (2) types of algorithms being used, (3) objectives being optimized, (4) evaluation methods and tools being used, and (5) popular publication forums over time.

The results of the first RQ showed that 14 out of 19 studies presented pure distributed VM consolidation algorithms, while 2 studies presented centralized algorithms with a distributed architecture for VM consolidation and 3 studies presented VM consolidation algorithms for geographically distributed data centers.

The answer to the second RQ showed that the existing dis- tributed VM consolidation approaches use four different types of algorithms, namely heuristics, metaheuristics, machine learning algorithms, and statistical approaches. Moreover, heuristics and metaheuristics are currently the most popular algorithm types. The most frequently used algorithm is distributed or coordinated local search heuristic, while Ant Colony Optimization (ACO) and greedy are the second most used algorithms. Only a small fraction of the existing distributed VM consolidation approaches can be categorized as using an online optimization technique. Hence, online optimization techniques are currently not sufficiently investigated for distributed VM consolidation.

For the third RQ concerning optimization objectives, we categorized the primary studies with respect to number and name of objectives and problem formulation. The results showed that nearly 3 of the primary studies optimize either one or two objectives and only a few approaches optimize more than two objectives. The existing distributed VM consolidation approaches optimize a total of 12 different objectives. The most popular optimization objective is minimizing energy consumption. Other popular objectives include minimizing Service Level Agreement (SLA) violations and minimizing the number of VM migrations. 9 out of 12 objectives are currently being addressed with only one or two algorithm types. Hence, the focus of future primary studies may be directed to investigate the remaining algorithm types for optimizing these objectives. About 5 2 of the studies presented a multi-objective or many-objective problem formulation with an Aggregate Objective Function (AOF), while the rest of the studies presented a single-objective problem formulation. None of the studies presented a pure multi-objective or many-objective problem formulation. Hence, future research may be directed to develop pure multi-objective and many-objective distributed VM consolidation approaches.

The results of the fourth RQ showed that experiment is the most common evaluation method for distributed VM consolidation approaches. The most common evaluation tool is simulation. Moreover, synthetic load patterns are the most common type of load patterns. Therefore, simulations involving synthetic load patterns are currently the most common evaluation tool. We also extracted data with respect to the other VM consolidation approaches that were used for a comparison of the results. The results showed that 9 studies did not contain a comparison of the results. Moreover, a total of 20 different approaches were used for a comparison of the results in the remaining 10 studies. In 9 out of 10 studies that contained a comparison of the results, the results of the proposed distributed VM consolidation approach were compared with centralized VM consolidation approaches. Therefore, there exists little evidence on how the different distributed VM consolidation approaches compare to one another. Hence, there is a need for more comparative studies involving multiple distributed VM consolidation approaches. We recommend that one or more of the 19 approaches studied in this SMS should be considered for more meaningful comparisons of the results in future studies.

The answer to the fifth RQ showed that the 19 studies were published in 17 different publication forums. Therefore, it is difficult to conclude whether or not there are any popular publication forums for distributed VM consolidation approaches. There is currently an increasing amount of interest on developing and evaluating novel distributed VM consolidation approaches for cloud data centers and publishing them in more rigorous publication forums.

Acknowledgments

The authors would like to thank Muhammad Usman at Blekinge Institute of Technology for his valuable comments on the review protocol. This work was supported by the Need for Speed (N4S) Research Program (http://www.n4s.fi) of the DIGILE, the Finnish Strategic Centre for Science, Technology and Innovation in the Field of ICT [grant number 2328/31/2013]. Adnan Ashraf also received a research grant from the Ulla Tuominen Foundation.

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