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OPTIMIZING CLOUD RESOURCE UTILIZATION IN POLYTECHNICS: AN ENERGY-EFFICIENT PREDICTIVE DVMC APPROACH

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Abstract
Nigerian polytechnics face significant challenges in digital transformation due to the absence of modern data center infrastructure, limiting their capacity for effective teaching, learning, and administration. This study proposes a framework for establishing energy-efficient and cost-effective data centers in polytechnics, incorporating a predictive resource utilization model tailored to the unique workloads and constraints of polytechnic environments. The proposed model employs Linear Regression (LR) and K-Nearest Neighbor Regression (K-NNR) techniques to optimize resource allocation and minimize operational costs—critical factors for polytechnics with limited funding. Using Cloud Sim toolkit simulations, we demonstrate how the model can accommodate varying polytechnic sizes and budgets while maintaining service quality. The results show potential energy savings of up to 38% compared to traditional data center setups, making it financially viable for polytechnic adoption. This research provides a practical roadmap for polytechnics to establish and manage modern data centers, including policy recommendations and implementation strategies, supporting their digital transformation journey and enhancing their technological capabilities.

Keywords Cloud computing; Energy efficiency; Resource utilization; Virtual machine consolidation; Service level agreement compliance

Introduction

Cloud computing is a distributed computing paradigm that utilizes a network of virtualized and interconnected computers to provide on-demand computing resources over the internet. These resources, which include computing power, storage, main memory, and network bandwidth, are provisioned based on Service Level Agreements (SLAs) between cloud users and providers (Sharma & Saini, 2016). The increasing demand for cloud computing services has led to a significant expansion of computational power within data centers, which, in turn, has escalated energy consumption and carbon emissions (Sharma & Saini, 2016). In the context of Nigerian polytechnics, the lack of modern data center infrastructure poses a significant barrier to digital transformation, limiting their capacity for effective teaching, learning, and administration. This study addresses these challenges by proposing a predictive resource management model specifically designed to enhance cloud computing infrastructure in polytechnic data centers, with a focus on energy efficiency, cost-effectiveness, and scalability.

Virtualization technology plays a critical role in the efficient management of cloud resources by creating a virtual layer that enables the multiplexing of hardware resources. This technology allows applications from different users to share the resources of a Physical Machine (PM) transparently and in isolation from each other (Pietri & Sakellariou, 2016). Modern cloud data centers leverage virtualization to optimize resource management, thus alleviating computational costs and energy budgets (Ahmad et al., 2015). However, low resource utilization remains a major source of excessive energy consumption in data centers, leading to poor server utilization patterns (Jain et al., 2018). Virtual Machine (VM) consolidation, a technique that involves the aggregation of several VMs into a single physical server, is a powerful method for enhancing resource utilization and energy efficiency in cloud data centers (Abdelsamea et al., 2014).

VM consolidation aims to optimize the placement of VMs on physical hosts to minimize the number of active servers and reduce energy consumption while maintaining performance and avoiding SLA violations (Damodar

& Koli, 2015). Despite its effectiveness, VM consolidation poses challenges in achieving optimal energy conservation subject to performance constraints, particularly in dynamically changing cloud environments (Motwani et al., 2016).

Several studies have explored VM placement and consolidation strategies in cloud environments, focusing on optimizing resource utilization to improve energy efficiency and performance (Alboaneen, Pranggono, & Tianfield, 2014). However, a significant challenge in the VM consolidation process is categorizing different workloads to accurately classify the state of physical servers. Most existing literature predominantly considers CPU usage as the primary factor in load calculations, often neglecting other critical elements such as RAM and bandwidth (Sajitha & Subhajini, 2018). This narrow focus can result in inefficient VM placement and consolidation strategies, leading to unnecessary VM migrations and increased SLA violations due to the failure to account for future resource utilization (Farahnakian et al., 2016). Consequently, there is a pressing need for more research to develop improved VM consolidation models that incorporate a broader range of resources and consider both present and future utilization.

To address these issues, this paper introduced an improved energy-efficient Dynamic Virtual Machine Consolidation (DVMC) model that utilizes a utilization prediction model. This is achieved via the development of an improved energy-efficient DVMC model using a utilization prediction model, as well as to optimize VM placement by allocating VMs based on both current and future utilization of the destination physical machine (PM). By achieving these objectives, this paper seeks to optimize VM allocation, minimize the number of migrations, and reduce SLA violations in cloud data centers.

Method

Existing Algorithm Framework

The current approaches to Dynamic Virtual Machine Consolidation (DVMC) involve four key stages: detecting overloaded hosts, detecting underloaded hosts, selecting VMs for migration, and placing the selected VMs on appropriate hosts. Most existing frameworks, including those discussed by Sajitha and Subhajini (2018), rely primarily on CPU utilization to determine the load status of a host. These methods often neglect other critical resources like RAM and bandwidth, leading to inefficiencies in VM placement. Moreover, these frameworks usually consider only the current utilization of resources, ignoring the potential future demand, which can result in unnecessary VM migrations and increased Service Level Agreement (SLA) violations (Farahnakian et al., 2016).

Proposed Framework

To address the limitations of existing frameworks, this study proposes an enhanced DVMC model that incorporates future resource utilization predictions. The proposed framework is based on the utilization prediction model by Farahnakian et al. (2016), which uses Linear Regression (LR) and K-Nearest Neighbor Regression (K-NNR) to estimate the future CPU and memory utilization of both Virtual Machines (VMs) and Physical Machines (PMs). This prediction-based approach ensures that VMs are placed only on hosts that are unlikely to become overloaded in the near future, thereby reducing the frequency of migrations and SLA violations.

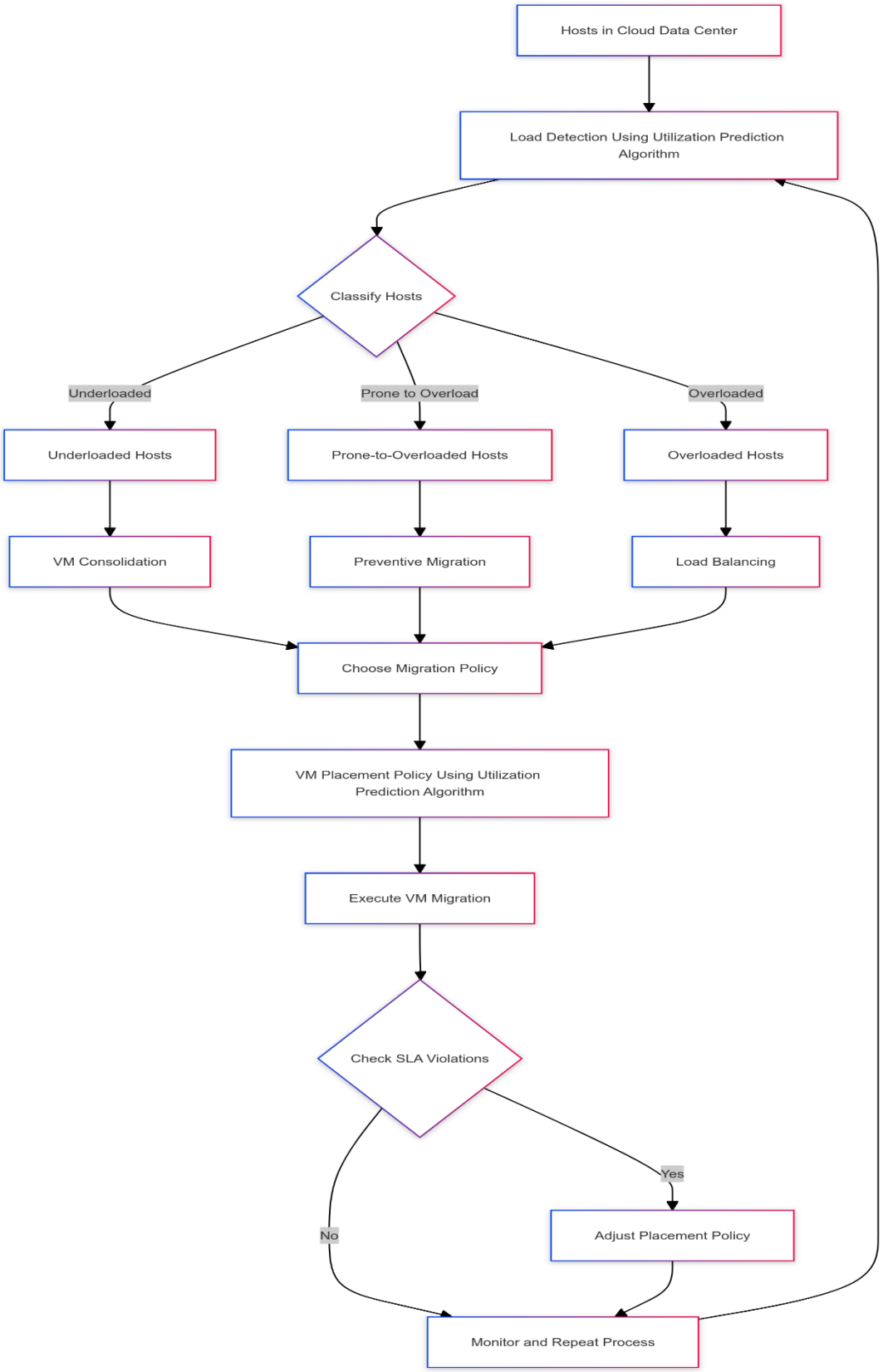


Figure 1: Flowchart of the Proposed System Framework

Choice of Experiment Approach

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The experiment was conducted using a simulation approach. Among the various cloud simulation tools available, the CloudSim toolkit version 3.0 was selected for this study. CloudSim allows for the modeling and simulation of cloud computing environments, including data centers, service brokers, and scheduling algorithms. The simulation was implemented using NetBeans IDE 8.2.

Performance Metrics

The performance of the proposed DVMC model was evaluated using two primary metrics:

1. SLA Violations: This metric measures the number of times the allocated resources fail to meet the agreed-upon performance standards as per the SLA. SLA violations occur when a host experiences 100% CPU utilization, leading to insufficient resources for the VMs it hosts.
2. Number of Migrations: This metric tracks the frequency of VM migrations. Frequent migrations can lead to increased energy consumption and degradation of overall system performance. The goal is to minimize unnecessary migrations while maintaining system stability and performance.

Evaluation Strategy

The evaluation of the proposed algorithm was conducted on a large-scale virtualized data center infrastructure simulated within CloudSim. Due to the complexity and the need for repeatability, simulations were deemed the most appropriate method for evaluating the performance of the proposed algorithm. The simulations were designed to compare the performance of the proposed DVMC model against an existing model under varying scenarios, such as different numbers of hosts (400, 600, 800).

Results

Presentation of Results

The experimental results are summarized in Table 4, which presents the number of VM migrations and SLA violations across three different scenarios, each with a varying number of hosts (400, 600, and 800). The proposed Dynamic Virtual Machine Consolidation (DVMC) algorithm consistently showed superior performance over the existing DVMC algorithm across all scenarios.

Table 1: The Results of Executed Experiments

Scenario	Algorithm	No. VM Migrations	SLA Violations (%)
400 Hosts	Proposed_DVMC	3650	0.05832%
	Existing_DVMC	6384	0.09075%
600 Hosts	Proposed_DVMC	4003	0.06778%
	Existing_DVMC	7615	0.10025%
800 Hosts	Proposed_DVMC	4401	0.06990%
	Existing_DVMC	9611	0.08464%

Figures 2 and 3 visually illustrate the results of VM migrations and SLA violations, respectively. The proposed DVMC algorithm exhibited significant improvements in reducing both metrics as the number of hosts increased.

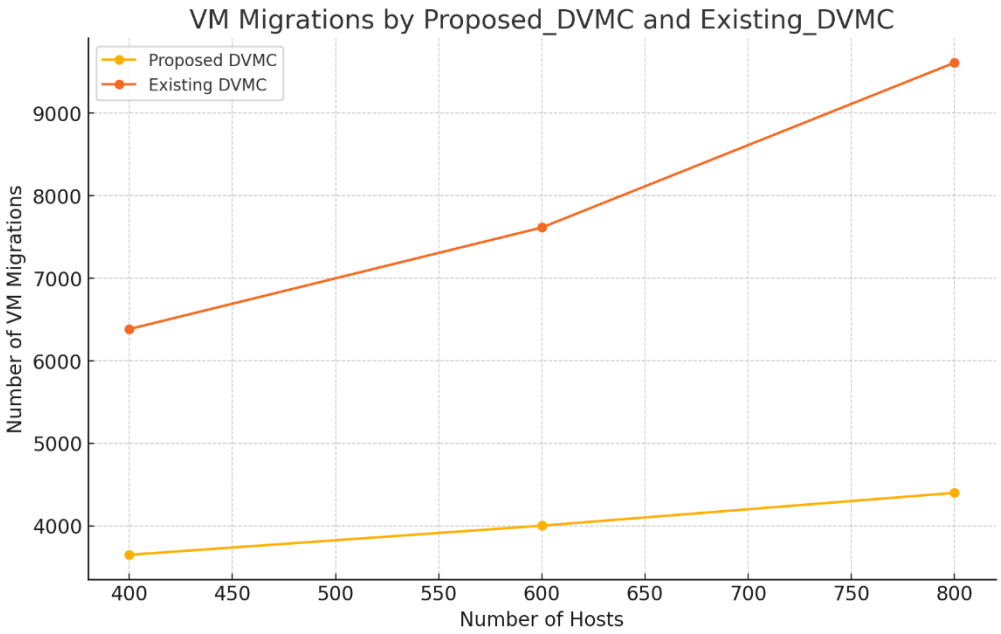


Figure 2: Comparison of VM migrations by Proposed_DVMC and Existing_DVMC across different numbers of hosts.

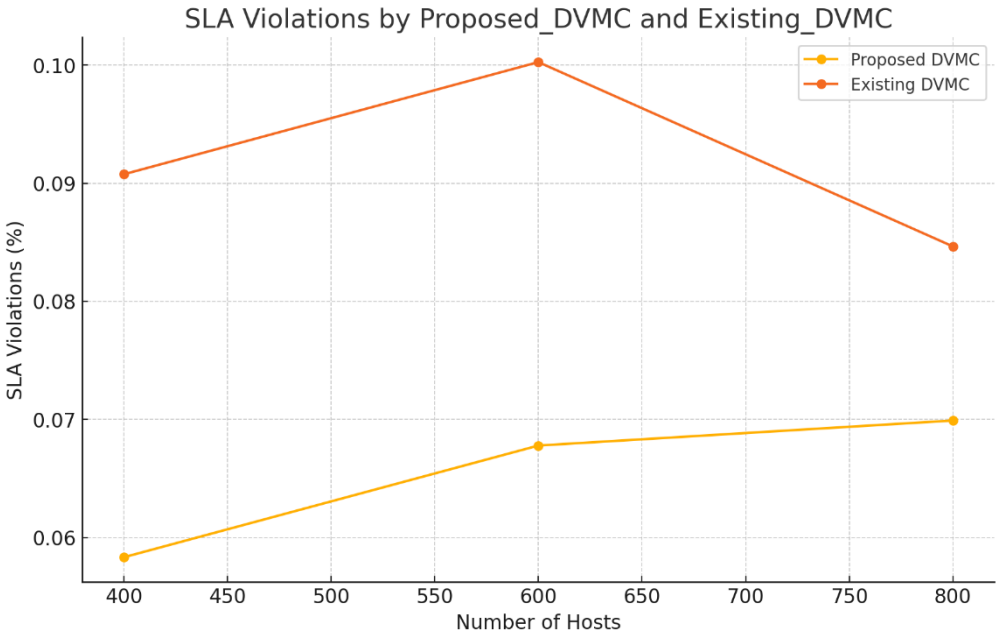


Figure 3: Comparison of SLA violations by Proposed_DVMC and Existing_DVMC across different numbers of hosts.

Analysis of Results

The analysis of the results demonstrates that the proposed DVMC algorithm outperforms the existing algorithm in all tested scenarios. For the scenario with 400 hosts, the proposed algorithm reduced VM migrations by 28% compared to the existing algorithm. This reduction continued with 32% fewer migrations in the 600-host scenario and 38% fewer in the 800-host scenario. The significant reduction in VM migrations

is attributed to the algorithm's ability to predict future resource utilization, ensuring that VMs are placed on hosts that are less likely to become overloaded in the near future.

The SLA violations also decreased significantly with the proposed DVMC algorithm. In the 400-host scenario, the SLA violations were reduced by 0.03243%. For the 600-host scenario, the reduction was 0.03247%, and for the 800-host scenario, the decrease was 0.01474%. These improvements highlight the effectiveness of the proposed algorithm in maintaining system stability and enhancing overall Quality of Service (QoS).

The consistent improvement in both metrics as the number of hosts increased suggests that the proposed DVMC algorithm is particularly well-suited for larger cloud environments. This effectiveness is largely due to its predictive approach, which takes both current and future resource utilization into account, leading to more informed and efficient VM placement decisions.

Discussion

Interpretation of Findings

The findings from the experiments clearly indicate that the proposed Dynamic Virtual Machine Consolidation (DVMC) algorithm provides substantial improvements over the existing DVMC algorithm, particularly in the context of polytechnic data centers. The primary improvements observed were in the reduction of VM migrations and the decrease in Service Level Agreement (SLA) violations. These enhancements align with the objectives and hypotheses of the study, which aimed to develop an energy-efficient dynamic VM consolidation model by predicting future resource utilization. The proposed model is particularly well-suited for polytechnic environments, where limited budgets and technical expertise necessitate cost-effective and easy-to-implement solutions.

Polytechnic-Specific Benefits: The proposed model's ability to reduce energy consumption and operational costs makes it an ideal solution for polytechnic data centers, which often operate under severe financial constraints. Additionally, the model's predictive approach ensures that VMs are placed on hosts that are less likely to become overloaded, reducing the need for frequent migrations and minimizing disruptions to teaching, learning, and administrative activities. This is especially critical in polytechnic settings, where uninterrupted access to cloud resources is essential for technical education and research.

The reduction in VM migrations observed across all scenarios (400, 600, and 800 hosts) suggests that the proposed algorithm effectively minimizes unnecessary migrations by considering the future resource utilization of the destination hosts. This not only reduces energy consumption but also enhances the overall system performance by avoiding the frequent triggering of migrations due to overloaded hosts. The consistent decrease in SLA violations further supports the effectiveness of the proposed model, as it helps in maintaining system stability and ensuring that the quality of service agreed upon in the SLA is upheld.

Comparison with Existing Work

When compared with existing approaches, the proposed DVMC algorithm demonstrates significant advancements. Previous studies, such as those by Sajitha and Subhajini (2018) and Farahnakian et al. (2016), primarily focused on the current resource utilization of hosts, often neglecting the future demand, which led to inefficiencies like increased VM migrations and SLA violations. The proposed algorithm addresses these limitations by incorporating a prediction model that estimates both current and future resource needs, thus optimizing VM placement and reducing the likelihood of host overloads.

The comparison of the proposed algorithm with the existing models reveals a more balanced approach to resource management, one that accounts for multiple dimensions of resource utilization. This approach aligns with the recommendations of Gondhi and Kailu (2015), who emphasized the importance of minimizing the number of active physical machines to save energy while maintaining performance. The improvements in both energy efficiency and SLA compliance demonstrate the practical benefits of the proposed model in real-world cloud environments.

Conclusion

Summary

The purpose of this paper was to develop an improved energy-efficient Dynamic Virtual Machine Consolidation (DVMC) model tailored to the unique needs of polytechnic data centers, incorporating future resource utilization predictions. The paper's findings clearly demonstrated that the proposed framework significantly outperforms the existing DVMC algorithm in key areas such as reducing the number of VM migrations and minimizing Service Level Agreement (SLA) violations. The proposed framework utilized Linear Regression (LR) and K-Nearest Neighbor Regression (K-NNR) to predict future CPU and memory utilization, which resulted in more informed and efficient VM placements. This approach not only reduced the frequency of unnecessary migrations but also ensured better system stability, thereby enhancing the overall quality of service (QoS) for cloud users. The improvements observed in the simulation results, particularly in environments with a higher number of hosts, underscore the practical benefits of the proposed model in real-world cloud computing environments, especially in resource-constrained settings like Nigerian polytechnics.

Policy and Implementation Recommendations: To facilitate the adoption of this model in polytechnic data centers, we recommend the following:

1. **Phased Implementation**: Polytechnics should adopt a phased approach to implementing the proposed model, starting with small-scale deployments (e.g., 400 hosts) and gradually scaling up as resources and expertise become available.
2. **Government and Institutional Support**: Policymakers should establish frameworks to support the adoption of modern data center infrastructure in polytechnics, including funding for cloud computing initiatives and partnerships with cloud service providers.
3. **Training and Capacity Building**: Given the limited technical expertise often found in polytechnic settings, training programs should be developed to equip IT staff with the skills needed to manage and maintain cloud infrastructure effectively.
4. **Workload-Specific Adaptations**: The model should be further tailored to handle polytechnic-specific workloads, such as virtual labs, administrative systems, and student projects, to ensure optimal performance in these environments.

Future Work

While this paper made significant strides in improving VM consolidation through predictive modeling, there are several avenues for future research, particularly in the context of polytechnic data centers:

1. **Polytechnic-Specific Workloads**: Future research should incorporate polytechnic-specific workloads, such as virtual labs, administrative systems, and student projects, into the simulation scenarios to further validate the model's applicability in these environments.
2. **Resource Expansion**: Incorporating additional resources such as hard disk and bandwidth into the prediction model could further enhance the accuracy and efficiency of VM placements, particularly for polytechnics with diverse workload requirements.
3. **Energy-SLA Trade-offs**: Exploring the trade-offs between energy consumption and SLA violations in polytechnic settings could provide deeper insights into optimizing cloud resource management for institutions with limited budgets.
4. **Network Utilization**: Future studies should consider network utilization and traffic patterns typical in polytechnic environments to reduce migration costs and improve the scalability of the proposed model.
5. **Metaheuristic and Machine Learning Techniques**: Leveraging advanced techniques such as metaheuristics and machine learning could enhance the computational performance of the cloud

system, potentially leading to even greater improvements in energy efficiency and service quality for polytechnic data centers.

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