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SURVEY ON ARCHITECTURES FOR SUSTAINABLE ENERGY-EFFICIENT GREEN CLOUD COMPUTING

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Abstract: Green cloud computing aims not only to lower the usage of energy but also to prominently cut down operational expenses. The main focus is to unify and efficiently manage a large pool of computational resources to serve individual applications effectively. A primary challenge in this context is the excessive energy consumption resulting from intensive processing tasks within densely interconnected data centers. These environments demand meticulous resource coordination and seamless operation to maintain both performance and sustainability. The article explores multiple dimensions of energy optimization, including workload scheduling, dynamic voltage scaling, and renewable energy integration. The article encompasses green data center design principles, cloud-based video streaming optimizations, and IoT network efficiency improvements. Several important issues surface when the number of tasks and the dynamic character of cloud resources rise: load balancing, resource allocation, task distribution, and system performance. Inaccurate scheduling causes problems like resource imbalance (either overuse or underuse) which causes service degradation or resource waste. Focussing on elements like resource use, dependability, makespan time, cost, energy consumption, availability, reaction time, and other important performance criteria, this work aims to explore and analyse the problems connected to job distribution among restricted cloud resources. This work presents a thorough literature assessment of task scheduling in cloud computing together with a new classification taxonomy and a comparison of several approaches.

INTRODUCTION

Although the exponential expansion of cloud computing infrastructure has given major advantages in terms of scalability and flexibility, it has also presented important problems especially related to energy consumption and sustainability. Based on estimates from the U.S. Energy Information Administration, data centres in the United States utilised around 139 billion kilowatt-hours yearly, making about 2% of the nation's total electricity use. Global digital sector consumption grew by 35% between 2014 and 2021 [1].This increasing trend is projected to continue as more companies adopt digital transformation and turn towards cloud-based infrastructures. Environmental studies draw attention to the notable ecological impact these technical developments bring about. Cloud computing is thought to account for around 2.5% of global greenhouse gas emissions at present. Typical data centres show a Power Usage Effectiveness (PUE) between 1.8 and 2.0, therefore highlighting very significant energy waste. With worldwide needs expected to reach 40 gigabytes by 2025, the need for power in this sector keeps increasing at an annual pace of 6%. In such buildings, around thirty percent of the entire energy usage is related to cooling systems alone [2].

Energy usage has been further raised by the growing inclusion of advanced technologies. Consequently, the demand of effective and sustainable energy management techniques has grown to be crucial. Studies show that using energy-conscious technologies—such as advanced cooling solutions combining liquid immersion and free-air cooling—may cut energy usage by up to 40% without sacrificing service dependability, which can remain as high as 99.999% [2].

Furthermore, the usage of renewable energy sources has shown to be a workable method for lowering environmental effect. Up to 35% of the carbon footprint can be reduced by hybrid energy systems combining traditional grid electricity with renewable sources such solar and wind [2]. Energy efficiency is not just an environmental issue but also a major financial need since, in data centres, energy expenditures usually account for 40% to 60% of total running expenses.This impact is especially severe in regions with high energy prices or unstable power infrastructures, where costs can rise by an additional 25% [3].

Green cloud computing aims to develop sustainable computing frameworks that offer energy-efficient services while reducing the environmental impact. As depicted in *Figure 2,* green IT practices span several domains such as proper power management, efficient data center design, server virtualization, eco-labeling of IT products, energy-efficient hardware, and recycling methodologies.

Figure 1. Applications of Fog Cloud Computing

Architectural implementations of green cloud computing typically encompass components such as parallel processing, virtualization, dynamic load balancing, and task scheduling. These architectural designs are designed mostly to lower energy losses, maximise the utilisation of the resources at hand, and guarantee consistent operational performance even under changing workloads [4][5][6]. Green computing thus becomes an essential junction point between environmental responsibility and modern technical development. Dealing with its difficulties calls both industry experts and university researchers as well as cloud infrastructure designers working together.

RELATED WORK

Domain specialists have carried out a lot of study to investigate ways to lower energy consumption in fog cloud computing architecture. Among these, paper [7] offers a clear answer for resource allocation in cloud systems. Their strategy consists of two layers: a green manager assigned to choose the most energy-efficient solution and a cloud manager in charge of spotting suitable computing resources. With an estimated energy expenditure of only 4200 watts, this hierarchical selection mechanism shows a notable performance gain and energy savings—effectively managing 500 service requests, hence surpassing the efficiency of traditional methods.

Data security stays a major issue of concern in parallel as well. In order to eliminate redundant data storage and guarantee safe data access inside cloud systems, Yongjian Liao and Ganglin Zhang [9] devised a novel encryption scheme. Complementing this, Riman Mandal and Manash Kumar Mondal [10] concentrated on energy-sensitive methods for virtual machine (VM) allocation and migration. Their approach, using trace-driven simulations, seeks to maximise energy use during VM reallocation—a particularly urgent necessity in large-scale cloud installations.

The work of Srimoyee Bhattacherjee and Rituparna Das [11] who thoroughly examined energy-conserving technologies in data centre environments reflects further efforts towards sustainable computing. Their prediction technology makes use of workload threshold analysis to enable energy-efficient virtual machine migration, therefore supporting environmental viability. Likewise, Qiheng Zhou and Minxian Xu [12] conducted a comparative analysis utilising the CloudSim modelling platform, therefore offering important new perspectives on the design and evaluation of adaptive, energy-efficient cloud resource management techniques.

Overview of Task Scheduling

Reducing power consumption in green cloud systems and improving system efficiency depend fundamentally on task scheduling. Commonly guiding scheduling techniques are three main goals: balancing computational loads, minimising makespan, and lowering running expenses.

Uniform distribution of tasks among the several computer nodes depends on load balancing. Reducing task latency, enhancing system responsiveness, and best hardware use depend on avoiding resource bottlenecks and server overload [13][14]. By means of a multi-objective strategy including fuzzy logic to represent user priority levels, therefore guaranteeing fair job allocation, a study by [15] solves the Dynamic Service Allocation (DSA) problem.

Makespan, defined as the total duration from the beginning of the first task to the completion of the final task in a batch, is another critical metric. Minimizing makespan enhances throughput and ensures efficient utilization of computing resources [16][17][18]. In [19], the integration of the Chameleon Search Algorithm and Remora Search Optimization Algorithm showcases improvements in exploration and exploitation trade-offs. These enhancements yield better task distribution and faster execution. The work in [20] proposes the IASOA model, which improves job throughput while minimizing makespan, evaluated across several benchmark algorithms.

Cost minimization remains a major factor for both cloud providers and consumers. The aim is to deliver performance while reducing operational costs [21]. In [22], researchers introduce a hybrid scheduling approach combining the Capuchin Search Algorithm (CapSA) and the Inverted Ant Colony Optimization (IACO) algorithm. This method enhances VM scheduling by considering execution time, energy usage, and task balancing. Another innovative approach in [23] employs the Whale

Optimization Algorithm, improved through a Gaussian Cloud Model (GCWOAS2), to avoid local optima and enhance global search ability—resulting in more efficient resource usage and better VM load distribution.

To achieve high performance in task scheduling, at least one objective function is necessary during the process. Table 1 represents a summary of scheduling objective functions observed in the selected studies.

Table 1: Summary of the Objective Functions of Task Scheduling

Reference	Makespan	Execution Cost	Throughput	Energy Consumption	Load Balance	Resource Utilization	Execution Duration	Load Distribution Variance	System Reaction Duration	Service Level Agreement Breach	Waiting Time
[13]	✔	✔	✔	-	-	✔	✔	-	✔	✔	-
[14]	✔	-	✔	✔	-	✔	-	-	-	-	-
[15]	✔	✔	-	-	-	✔	✔	-	-	-	-
[16]	✔	✔	-	✔	-	✔	✔	-	-	-	-
[17]	✔	✔	-	-	✔	✔	✔	-	-	-	-
[18]	-	✔	-	✔	✔	✔	-	-	-	-	-
[19]	✔	✔	-	✔	✔	✔	✔	-	-	-	-
[20]	✔	-	✔	✔	✔	✔	-	-	✔	-	-
[21]	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
[22]	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
[23]	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔

As shown in Figure 2, several tools support the simulation and testing of scheduling algorithms in cloud environments. Tools such as CloudSim, IOTSim, WorkflowSim, and EdgeCloudSim enable detailed modeling of energy consumption, workload distribution, and virtual resource allocation. MATLAB, TensorFlow, and Vmware-Vsphere offer versatile environments for designing and testing optimization algorithms. These tools are critical for validating proposed solutions before real-world deployment.

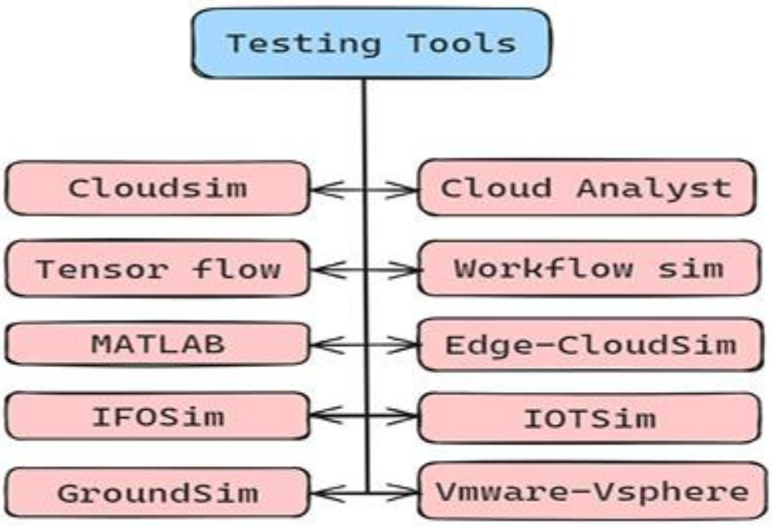

Figure 2. Scheduling Tools for Testing

CONCLUSION

Cloud computing continues to revolutionize modern IT infrastructures with its scalable, pay-per-use service model. However, the environmental implications of rising energy demands necessitate the development of sustainable computing paradigms. This survey has reviewed various scheduling strategies that optimize energy consumption, reduce costs, and enhance system performance.While numerous algorithms have demonstrated effectiveness in addressing individual optimization objectives, no single method has yet achieved comprehensive efficiency across all metrics. Hybrid scheduling algorithms that integrate multiple heuristic strategies offer a promising path forward.Using artificial intelligence to build context-aware, real-time adaptive systems will help future studies concentrate on the dynamic integration of job scheduling and virtual machine consolidation. Realising the full possibilities of green cloud computing and guaranteeing its sustainability in the era of pervasive digital services depend on such developments.

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