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Long Paper

Energy-aware and Carbon Footprint Optimization Model for Virtual Machine Placement in Data Centres – A Systematic Literature Review

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Abstract

Purpose—The rapid adoption of cloud resources and their applications has increased energy consumption and carbon footprint emissions in data centres, raising significant environmental concerns. One key strategy to address this challenge is optimizing the allocation of resources and applications, such as virtual machines (VMs), within data centre architectures. Virtual Machine Placement (VMP), which involves selecting the best physical machine (PM) to host user-requested VMs, is critical in reducing energy consumption and carbon emissions.

Method – This study undertakes a systematic analysis of the requirements for energy-aware and carbon footprint (CFP) optimization in VMP within cloud data centres. A comparative approach is employed to evaluate the salient features of various VMP methods, examining their ability to meet energy efficiency and sustainability goals. VMP is identified as a complex combinatorial optimization problem that is NP-Hard, necessitating innovative strategies to achieve optimal solutions.

Conclusion – Despite advancements in energy-efficient and CFP-optimized VMP methods, unresolved challenges remain, such as balancing energy savings with service quality and scalability. These challenges highlight the need for continued exploration of innovative techniques to address the complex nature of VMP problems.

Recommendations – Future research should focus on hybrid optimization techniques, leveraging metaheuristic approaches to improve energy efficiency and sustainability. Moreover, developing real-world prototypes and frameworks to validate theoretical models can bridge the gap between research and practical implementation, paving the way for sustainable cloud computing solutions.

Practical Implications – This review highlights effective energy-aware and CFP strategies for VMP in CDC. Categorizing and analyzing recent developments provides practical insights for cloud service providers and data centre operators to implement efficient VMP methods. These findings enable better resource allocation, reduced operational costs, and minimized environmental impact, aligning with sustainability goals and improving the overall performance of cloud infrastructure systems.

Keywords –– carbon footprint, virtual machine placement, cloud data centre

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INTRODUCTION

Cloud computing is a computing model that leverages the Internet for the dissemination of information, software, and resources to personal computers and other devices as needed (Singh & Agnihotri, 2018). Authors (Jeevitha & Athisha, 2023) focusing on the same subject of CDC, stated the primary objective of cloud computing is to maintain and structure extremely large data centres or data sets. It must be noted that these data sets consist of numerous servers that consume a significant amount of energy. (Katal et al., 2023) agreed that Cloud computing, from its conceptualization to its energy efficiency, has been a topic of extensive discourse and since 2006, cloud computing has evolved into a commercial and economic paradigm and is currently the most influential technology in the IT industry. Hence in its real-life application authors (Buyya et al., 2024) noted that cloud computing has emerged as a vital infrastructure for contemporary society, akin to electricity grids and transportation networks. Serving as the backbone of the modern economy, it delivers computing services on a subscription basis, accessible anytime and anywhere, with a pay-as-you-go model.

The amount of carbon dioxide (CO2) emitted from a Cloud Data Centre (CDC) energy source is known as the "ICT carbon footprint" with severe environmental impact (Talebian et al., 2020). According to other recent research conducted by Greenpeace (International, 2022), the carbon footprints (CFP) left by the information technology industry account for 2% of global greenhouse gas emissions. (Panwar et al., 2022) predicted that the energy consumption of CDCs alone will rise from 200 TWh in 2016 to 2967 TWh in 2030 hence an increase in CFP emissions.

Statistically, it is a well-established fact currently that data centres that host Cloud services on a global scale are responsible for consuming a substantial amount of energy, surpassing the energy consumption of most countries (Buyya et al., 2024). This surge in energy usage is exemplified by the expected rise in energy consumption of data centres from 200 TWh in 2016 to a monumental 2967 TWh by the year 2030 (Katal et al., 2023). (Pandey & Singh, 2023) concurred that the amount of energy that will be consumed is expected to increase to 8000 terawatt hours (TWh) by the year 2030 which would result in the emission of 150 million tons of carbon.

The administration of data centres, which is the basis for cloud computing, must address the crucial issue of energy efficiency. The placement of VMs significantly affects a data centre's resource utilization and energy efficiency (Hormozi et al., 2022). These days, data centres are getting bigger and bigger, which has resulted in a sharp rise in power consumption and cooling costs. In a data centre, the three primary categories of equipment that use electricity are physical machines (such as servers), cooling systems, and network equipment (Xing et al., 2022). Hence data centers now have the largest carbon impact ever (Durairaj & Sridhar, 2023).

There is an urgent need to reduce CDC energy intake since the amount of energy used by Cloud Data Centers (CDCs) has expanded dramatically in this digital age. To save energy, large data centres frequently use effective virtual machine placement (VMP) techniques and the consolidation of virtual machines (VMs) (Parthiban et al., 2022). Typically, they each use 40–55 percent, 15–30 percent, and 10–25 percent of the total power. Less energy is used and datacenter efficiency is increased with the right set of PMs for hosting VMs. As a result, it is essential to solve the virtual machine placement (VMP) problem, which involves placing VMs as efficiently as possible (Xing et al., 2022).

LITERATURE REVIEW

The term "virtual machine placement" (VMP) refers to the method by which virtual machines (VMs) are mapped to physical machines (PMs) in a data centre. The primary objective of VMP is to minimize carbon footprint emissions (Alsadie, 2022). To find the best VM to PM (physical machine) mapping, a VM placement method must consider both the initial VM placement and the VM location following migration for re-optimization (Usmani & Singh, 2016; Vatsal & Agarwal, 2021). The unpredictable arrival patterns of requests for virtual machine instances combined with the expansive size of cloud data centres make it a challenging problem to solve. This makes it difficult to find the best or near-best physical machines to match a particular virtual machine (Alsadie, 2022). In several research publications such as (Shaw et al., 2017; Madhumala & Tiwari, 2020; Khoshkholghi et al., 2017).

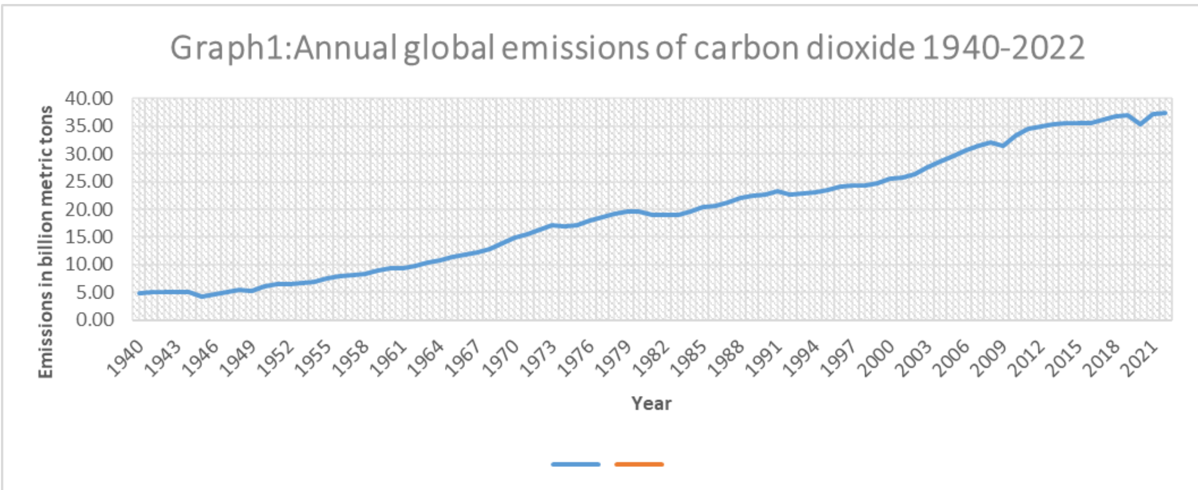

Figure 1. Annual global emissions of carbon dioxide 1940-2022

One of the primary concerns related to data centres is the increasing energy usage, leading to environmental contamination (T Renugadevi et al., 2020). Moreover, the escalation of energy consumption exerts a substantial influence on the environment as a result of carbon dioxide emissions. The consolidation of Virtual Machines (VMs) into the minimum number of Physical Machines (PMs) is widely regarded as an effective approach to power consumption management (Ibrahim et al., 2020). Recent studies have shown that an increase in energy consumption is associated with the CO2 emission footprint of data centres which has exhibited a concerning escalation over the last decade (Nahhas et al., 2019).

Table 1. Comparative relationship between energy efficiency and carbon footprint with the main objective

Author	Objective	Energy efficiency	Carbon footprint optimization
(Wadhwa & Verma, 2014a)	To decrease cloud energy use and carbon emissions.	✓	✓
(Nam et al., 2016)	To control the energy status of network devices and servers	✓	
(Khosravi et al., 2017)	To improve VM placement, we examine characteristics that significantly impact energy and carbon footprint costs.	✓	✓
(Justafort et al., 2018)	The goal is to tackle the issue of VM placement in InterCloud computing environments to reduce carbon footprint.	✓	✓
(Justafort et al., 2019)	Solve the InterCloud workload placement challenge to reduce the carbon footprint of computing environments.	✓	✓
(Justafort et al., 2014)	Addressing VM location in InterCloud computing environments to reduce carbon footprint.		✓
(Aldossary & Alharbi, 2021)	We present a multi-level MILP model to reduce data centre CO2 emissions by optimizing resource use and VM placement in fog-cloud situations.		✓
(Vaneet Kumar & Jindal, 2021)	To improve the energy efficiency of massive data centres	✓	
(Rawas et al., 2022)	It allocates VMs and uses greedy policies to deploy them on optimal hosts to reduce data transmission latency, CO2 emissions, PUE, and energy consumption.	✓	✓
(Abbasi-khazaei & Rezvani, 2022)	Collaboration to reduce energy costs and schedule	✓	✓
(Darshini et al., 2022)	To reduce execution time and energy usage.	✓	
(Bharathi et al., 2017)	concept of cloud-based scheduling with two levels	✓	
(Deepika & Dhanya, 2023)	To achieve increased consolidation of PMs in SMSDCs, which will contribute to being power- and carbon-aware.	✓	✓
(Zhao & Zhou, 2022)	To reduce carbon emissions by increased use of RES, temporal-variable wind speed, and spatially variable CFRs.	✓	✓
(Khosravi et al., 2013)	to lower Cloud computing energy and carbon footprint	✓	✓
(Khodayarseresht et al., 2023)	Reduce energy consumption and carbon emissions in cloud data centres without compromising service quality.	✓	✓
(Laghrissi et al., 2019)	Effective management of virtual resources, workloads, and mobility patterns.	✓	✓
(T. Renugadevi et al., 2020)	Balance server load and adjust cooling load based on workload.	✓	✓
(Larumbe & Sanso, 2016)	tabu search	✓	✓

The Statista report (Tiseo, 2023) from Graph 1 above describes that in the year 2021, the world's emissions of carbon dioxide from fossil fuels and industrial processes totalled 37.12 billion metric tons ($GtCO_2$). It is anticipated that emissions will have increased by 0.9 per cent in 2022, reaching 37.5 $GtCO_2$ — the highest level ever recorded. Since 1990, there has been a more than 60 per cent increase in CO_2 emissions across the globe. China and the United States produced 11.47 and 5.01 $GtCO_2$ in 2021, respectively, making them the two largest producers of global emissions. The reason is that various authors (Sabyasachi & Muppala, 2022) (Teng et al., 2017) (You et al., 2017) agreed with Statista that the economic growth of nations all over the world, particularly in Asia, has been one of the primary contributors to the increase in greenhouse gas emissions which is directly proportional to demand of resources in data centres. Also report from (IEA, 2023) did indicate similar findings from Statista that for instance, China did not always rank as the top emitter in the world; nevertheless, due to the country's rapid economic development and industrialization in the most recent decades, emissions there have skyrocketed. The growth in CO_2 emissions in China was greater than 400 per cent between the years 1990 and 2021. A comparable increase in emission levels was observed in India during the same period. In contrast, the amount of carbon dioxide in the atmosphere in the United States has decreased by more than six per cent since 1990.

Panwar et al. (2022) predicted that the energy consumption of CDCs alone will rise from 200 TWh in 2016 to 2967 TWh in 2030 hence an increase in CFP emissions. With the increasing prevalence and use of cloud computing services, CDC service providers and academic institutions alike, are now required to make decisions that are not only sustainable but also environmentally friendly (Kinkar et al., 2022). Many studies have been conducted on the topic of optimizing VMPs from the points of view of monetary savings, energy savings, task workflow efficiency, service quality, and resource transmission (Jumde & Dongre, 2021) (Abdessamia et al., 2020). Improving energy efficiency and carbon footprint in data centres can be accomplished by implementing a suitable VMP scheme that minimizes powering costs at the hardware level (Challita et al., 2017).

Authors (Khosravi et al., 2017) acknowledged that Cloud data centres have a significant impact on the environment due to their high energy consumption and associated big carbon footprints. The carbon intensity of green energy, specifically solar and wind power, is considered to be negligible. In contrast, brown energy derived from polluting energy sources exhibits varying levels of carbon intensity, contingent upon the specific type of fuel utilized in the electricity generation process. Due to the fluctuating availability of green energy during the day, a single data centre can get off-site grid power from many providers with varying carbon intensity. In addition, carbon taxes are imposed as a means to mitigate the impact of emitted CO_2 and greenhouse gases (GHG) on climate change (Khosravi et al., 2017). Taking into account the carbon tax that is imposed on the carbon that is emitted causes the cost of energy and carbon to play a significant part in the operational costs of data centres. They did mention that by analyzing the characteristics that have the most significant impact on the total cost of energy and carbon footprint you can come up with an effective strategy for the placement of virtual machines. Agreeing with the vm placement solution authors (Larumbe & Sanso, 2016) illustrated putting virtual machines (VMs) in data centres that run on renewable energy is a significant step toward finding a solution to this issue. They formulated their optimization problem as a Mixed Integer Linear Programming (MILP) model, The same formulation approach was used by authors (Justafort et al., 2014 2018)which seeks to reduce operating costs while simultaneously obeying restrictions on the Quality of Service (QoS), power consumption, and CO_2 emissions. On the other hand, they agreed with (Panwar et al., 2022), that the ever-increasing energy consumption of the cloud has generated concerns regarding the influence it will have on CO_2 emissions and global warming.

To narrow down the world greenhouse gas emissions to the ICT sector from the chart, data centres take the lead in emissions as indicated (Laricchia, 2023) report. In the ICT sector this has drawn the interest of many researchers given the current state of affairs regarding climate change, a topic that has gained a lot of attention is the carbon footprint left by information and communications technology (Li et al., 2022) industry. The part of this industry that is responsible for the most substantial contributions of greenhouse gases is the data centre segment, which accounts for 45 per cent of the total, followed by the communications network segment, which accounts for 24 per cent.

To address the aforementioned carbon footprint emission in data centres, many authors have suggested various solutions. (T Renugadevi et al., 2020) Did state that efficient management of server power usage for a given workload has the potential to enable data centres to effectively mitigate their carbon emissions. However, it is evident from the noted reports(Kilgore, 2023; Laricchia; Tiseo)that more mitigation measures are required to optimize the carbon footprint in data centres. This is the motivation behind conducting this systematic review, the main objective being to critically analyze the requirements for carbon footprint (CFP) optimization in cloud data centre VMP. Additionally, we aim to conduct a comparative study of salient features of VMP methods of meeting those requirements, and how evaluation is done to each of them in the view of noting potential future research directions.

The State-of-the-art VMP-CFP CDC

Within this particular section, we explore VMP-CFP CDC methods. A comprehensive analysis is conducted to identify and characterize various approaches found in the existing literature for each category. The selection of these methods is based on their relevance and alignment with the specific objectives employed in the research as indicated in Table 1.

From Table 1, you can identify that for the carbon footprint to be reduced in data centres, the energy aspect must be interrogated as stated by the authors (Khosravi et al., 2013) (Wadhwa & Verma, 2014a) in their objective to reduce both energy and carbon footprint. The environment is positively impacted in a variety of ways by energy efficiency. It has a significant impact on lowering greenhouse gas emissions, both the direct emissions caused by the combustion or use of fossil fuels and the indirect emissions reductions brought about by the production of electricity. Authors (Khosravi et al., 2017) (and Justafort et al., 2018) brought an aspect of virtual machine placement in the reduction of energy and carbon footprint in the data centre. In their main objective to achieve optimal VM placement, they had to investigate the factors that have a major bearing on the prices of energy and carbon footprint. (Rawas et al., 2022) considered in his objective the allots of virtual machines (VMs) and using greedy strategies to deploy them on ideal hosts to cut down on data transmission latency, CO2 emissions, power use effectiveness (PUE), and overall energy consumption.

Over the past decades, researchers have made significant contributions toward enhancing the problem of VM placement and consolidation. Their efforts have aimed to maximize resource utilization, power consumption, and carbon footprint emissions in data centres, all while ensuring performance limitations are upheld. From Table 2, the four main categories of algorithms commonly employed in problem-solving are heuristics, meta-heuristics, deterministic algorithms, and hybrid techniques. The present study examines various ways that have been developed to tackle the issue of CFP optimization through virtual machine (VM) placement in data centres.

Heuristic Methods

In this section, we analyze the carbon footprint optimization and virtual machine placement problem which has been addressed through suggesting heuristic methods. You will discover that in the last five decades, the concept of 'heuristics' has garnered significant interest across a range of disciplines including psychology, cognitive science, decision theory, computer science, and management research (Hjeij & Vilks, 2023).

The allocation of virtual machines can be conceptualized as a bin-packing problem, in which the virtual machines are represented as items and are placed on a minimal number of physical machines, represented as bins (S & Nair, 2019). When determining the placement of a virtual machine, several factors related to the physical computer's resources, including the CPU, memory, network, and storage, are taken into account. The VM consolidation problem is widely acknowledged to be NP-hard due to its inherent complexity(Khosravi et al., 2017) (Zhao & Zhou, 2022). Consequently, there was a further exploration of numerous heuristic-based methodologies aimed at enhancing the carbon efficiency activities within the cloud data centre.

In solving the virtual machine placement problem (Rawas et al., 2022) designed the LECC model to identify the optimal placement of virtual machines (VMs) while considering two primary objectives: lowering the expenses associated with users' data transfers and reducing the overall carbon emissions cost, all while ensuring that the requisite quality of service (QoS) is maintained. (Zhao & Zhou, 2022) also stated that the carbon footprint aspect in data centres is mostly attributed to the release of greenhouse gases, particularly from the combustion of fossil fuels, commonly referred to as brown energy, resulting in environmental emissions.

Table 2. Taxonomy (categories of the algorithm used)

Method/Author	Heuristic	Metaheuristic	Deterministic	Hybrid
(Khosravi et al., 2013)	✓			
(Justafort et al., 2014)			✓	
(Wadhwa & Verma, 2014a)	✓			
(Nam et al., 2016)				
(Larumbe & Sanso, 2016)	✓			
(Bharathi et al., 2017)				✓
(Khosravi et al., 2017)	✓			
(Justafort et al., 2018)			✓	
(Laghrissi et al., 2019)			✓	
(Justafort et al., 2019)		✓		
(T. Renugadevi et al., 2020)	✓			
(Vaneet Kumar & Jindal, 2021)	✓			
(Aldossary & Alharbi, 2021)				✓
(Rawas et al., 2022)				✓
(Abbasi-khazaei & Rezvani, 2022)		✓		
(Darshini et al., 2022)		✓		
(Zhao & Zhou, 2022)	✓			
(Khodayarseresht et al., 2023)				
(Deepika & Dhanya, 2023)				✓

In addition, Rawas et al. (2022) made use of the heuristic MF-LECC algorithm, aimed at identifying the optimal selection of data centres (DCs) by minimizing the rates of lc, PUE, and CO2 emissions. This action they took was to enhance the efficiency of the chosen data centre's energy usage by condensing the requested virtual machines onto a reduced number of active hosts. By authors (Zhao & Zhou, 2022) describing virtual machine placement as a bin-packing problem, went ahead and proposed an EFP algorithm comprising two consecutive heuristic algorithms. Their primary objective was to minimize the total energy usage by selecting the appropriate destination physical machine (PM) for virtual machine (VM) requests. On the other hand (Aldossary & Alharbi, 2021) classified this same problem as a non-deterministic polynomial (International, 2022) a hard task. In their process of determining the optimal location of applications within a fog-cloud architecture, to minimize carbon emissions, they did give a practical solution example as follows; let us consider a scenario where 'a' represents the number of applications and 'c' represents the number of locations in a fog-cloud architecture. In this case, the total number of alternative sites that may be explored to identify the ideal placement, resulting in the smallest amount of CO_2 emissions, can be calculated as Pc xD1 .x–cWx/W. Hence, they noted the practicality of employing Mixed Integer Linear Programming.

MILP for solving extensive problem instances is limited. Hence, a heuristic is employed to facilitate the execution of a real-time implementation. Additionally, the heuristic serves to validate the outcomes generated by the Mixed Integer Linear Programming (MILP) model. Therefore, they devised a heuristic approach known as the Heuristic of Green Applications Placement over the Fog-Cloud Architecture (HOGAP-FC). This example was quite different from the approach (Zhao & Zhou, 2022) that was based on the existing Power-Aware Best-Fit Decreasing (PABFD) method. However, the anticipated energy usage in the foreseeable future was being taken into consideration. Subsequently, a unique algorithm referred to as EFP was introduced to effectively manage the trade-off between energy consumption and carbon footprint. That algorithm incorporates predictive renewable energy and also considers the workload of virtual machines (VMs). Furthermore, the study incorporated five alternative variations of the suggested methodology as baseline algorithms. These versions encompass distinct aspects that exert an influence on the carbon emissions of data centres.

Authors (T. Renugadevi et al., 2020) suggested techniques involving the allocation of new virtual machines (VMs) to servers that are capable of accommodating them. This allocation process aims to achieve three objectives: (i) the creation of carbon-efficient clusters by considering the Power Usage Effectiveness (PUE) and carbon footprint rate (CFR); (ii) the optimization of server power efficiency by determining the best operating frequency; and (iii) minimizing the overall increase in power consumption resulting from the allocation of new VMs. Authors (Khosravi et al., 2017) presented Carbon Footprint-Aware with the Dynamic PUE (FA-DP) algorithm in their study based on the ECE algorithm previously proposed in their previous study. However, unlike the previous work, this approach takes into account the dynamic nature of the Power Usage Effectiveness (PUE) and carbon intensity. The algorithm chooses the data centre that has the lowest value of RtE * PUE(Khodayarseresht et al.; Mittal et al., 2021) from the set of data centres B, G, and O.

Authors (Wadhwa & Verma, 2014a) presented a novel method known as the Carbon Efficient VM Placement and Migration Technique (CEPM). Our approach distinguishes itself from previous techniques by addressing the optimization of virtual machine (VM) placement in federated cloud data centres with varying carbon footprints. They accomplished this by considering the current server utilization in each data centre and conducting VM migrations as necessary to maximize energy efficiency. The technique proposed adhered to the distributed cloud architecture, wherein data centres are federated across several geographic regions. The carbon footprint rate of each data centre inside the distributed cloud architecture varies depending on its energy resource.

Authors (Khosravi et al., 2013)) present the Energy and Carbon-Efficient (ECE) VM placement algorithm, which was a modified version of the best-fit heuristic for allocating VMs in the data centre, cluster, and host with the least carbon emissions, Power Usage Effectiveness (PUE), and minimal rise in power consumption of physical servers. The broker is responsible for receiving a virtual machine (VM) request and subsequently determining the most suitable physical server for hosting the VM. The primary goal of this initiative is to reduce the carbon emissions and energy consumption of data centres. The algorithm's complexity is mostly determined by the amount of virtual machine (VM) requests and the sorting function for hosts, due to the limited number of data centre sites and clusters available for the Cloud provider. The algorithm's overall time complexity can be expressed as O(such as log(h)).

Power-efficient techniques with bin-packing heuristics dubbed Power Efficient First-Fit Decreasing (PEFFD) and Power Efficient Best-Fit Decreasing (PEBFD) are presented to increase energy efficiency by reducing SLA violations and the number of VM migrations while assuming that the CPU uses the majority of the energy. To decrease SLA violations and VM migrations, a new bin-packing strategy dubbed a Medium-Fit (MF) is created. They have simply considered CPU use, like the majority of previous research. Additionally, they add that to execute the suggested methods practically, peak host power must be determined (Nahhas et al., 2021).

Metaheuristic Methods

Meta-heuristics refer to a class of high-level heuristics that are employed to acquire a satisfactory solution when faced with constraints such as limited knowledge and resources. Evolutionary algorithms encompass a category of search algorithms that are commonly employed in the field of meta-heuristic optimization. The utilization of Genetic Algorithm (Bharathi et al., 2017), Flower Pollination Algorithm (FPA) (Darshini et al., 2022), Modified Memetic algorithm (MA) (Abbasi-Khazaei & Rezvani, 2022), and Particle Swarm Optimization (PSO) (Deepika & Dhanya, 2023) are prevalent in the field of CFP VMP in data centres.

Metaheuristic algorithms—based on the collective intelligence of colonies of ants, termites, bees, birds, and other organisms—are the most exciting and widely used metaheuristic algorithms (Singh & Choudhary, 2020). SI algorithms can be used to solve a wide range of optimization and NP problems, including dynamic optimization and multi-objective optimization (Adedeji et al.). Its success can be attributed to the fact that it makes use of knowledge that several agents frequently share, allowing for cycles of self-organization, co-evolution, and learning to provide the best possible outcomes (Singh &

Choudhary, 2020). Below is the summary table of some of the commonly used Swarm-intelligence algorithms.

Considerably, the well-known Particle Swarm Optimization (PSO and Ant Colony Optimization (ACO) served as the primary sources of inspiration for the initial conceptualization and subsequent establishment of swarm intelligence (SI) (Osaba & Yang, 2021). These two algorithms are responsible for the success of SI, serving as the foundation and the primary driving force behind further research (Osaba & Yang, 2021).

While PSOs are simple to implement, reliable, fast to converge, computationally efficient, and problem-solving. These are the disadvantages of PSO. For example, difficult-to-define starting design parameters, scattering issues, premature convergence, and optimization in complex situations. (Mittal et al., 2021). The problem of multimodal optimization was addressed by (Wang, 2017), who offered a solution. Because of the integral arbitrariness of PSO, PSO is prone to dropping into local minima. Using the adaptive parameter control technique in multimodal situations improves PSO performance. It should be noted that the PSO's control parameters have a significant impact on performance. As a result, the dependence on the parameters may be reduced by the application of adaptive technology (Mittal et al., 2021). In addition, in comparison to the standalone PSO algorithm, the hybrid PSO or modified PSO design, which is set by the application, is preferable and provides the best possible performance (Mittal et al., 2021).

Deterministic Methods

Authors (Justafort et al., 2014) present a novel mathematical formulation that introduces a mixed integer programming problem as a technique for determining the placement of resources in the InterCloud. The objective of this issue is to minimize the total carbon footprint of the InterCloud. The suggested formulation offers a precise assessment of carbon footprint by employing joint optimization strategies, including workload consolidation and maximizing cooling efficiency. This approach takes into account the environmental sustainability of data centres and the dynamic nature of IT equipment cooling fans.

Authors (Justafort et al., 2018) in their research aimed to examine the issue of Virtual Machine (VM) deployment inside an InterCloud, specifically focusing on the potential for reducing carbon emissions in this computing environment. Their study presented a mathematical concept to reduce Greenhouse Gas (GHG) emissions from data centres. The proposed approach formulates the placement problem as a Mixed-Integer Nonlinear Programming (MINLP) problem, intending to minimize the carbon footprint of InterCloud. The formulation being proposed offers a precise assessment of carbon footprint by employing joint optimization techniques. These techniques include intelligent and performance-conscious workload consolidation, as well as the maximization of cooling efficiency. Additionally, the formulation takes into account the environmental sustainability of data centres and the dynamic characteristics of equipment cooling fans.

Deterministic optimization approaches prioritize the identification of global solutions by leveraging the analytical characteristics of a given problem. The guarantee of solution quality is a distinguishing feature of the generated solutions, in contrast to heuristic methods. However, the computational time required to compute the results for a big optimization issue is substantial. The VM packing problem is being addressed using a constraint programming approach in reference(S & Nair, 2019) (Laghrissi et al., 2019). The proposed methodology considers the combined factors of energy usage, service level agreement (Rafique et al., 2019) requirements, and utility functions. The authors believe that the utilization of the Constraint programming approach offers numerous benefits in comparison to heuristics-based approaches, particularly in the realm of creating optimal solutions. The study presented in reference (Rawas et al., 2018) examines the concept of a flexible energy-aware virtual machine (VM) allocation and consolidation inside a federated cloud data centre. The energy-aware placement of virtual machines (VMs) is computed using the Constraint Programming (CP) paradigm and the Entropy open-source package.

Service Level Agreements (SLAs) are expressed as limitations. The essential component of the architecture is the optimizer, which operates on the CP engine and receives SLA constraints and a Power Objective function as inputs. The conducted tests have demonstrated that a significant quantity of energy may be conserved through the implementation of this strategy, while also limiting carbon dioxide (CO_2) emissions. The management of grid-based data centres is optimized using linear programming techniques and integer optimizers, as discussed in the reference (Justafort et al., 2018). The objective is to allocate a collection of tasks to a group of available resources. The scheduling strategy utilizes consolidation approaches to identify a solution that is close to optimal in terms of economic benefits, resulting in reduced violations of Quality of Service (QoS) and minimal power consumption. The methodology described in this study involves the utilization of migration techniques and the deactivation of idle physical devices to effectively reduce energy consumption. The computational complexity of an integer linear program is widely recognized as being challenging. This approach has the potential to yield solutions that are close to optimal by comprehending the system and formulating a well-defined problem statement with appropriate restrictions.

Deterministic optimization approaches prioritize the identification of global solutions by using the analytical characteristics inherent in a given problem. The guarantee of solution quality is a distinguishing feature of the acquired solutions, in contrast to heuristic methods. However, the computational time required to obtain answers for a big optimization issue is substantial. The VM packing problem is being addressed using a constraint programming method (Nahhas et al., 2021).

Hybrid Methods

The phrase "hybrid approach" is used to describe a solution method that incorporates several allocation policies for virtual machine consolidation. The hybrid approach refers to the integration of heuristic algorithms, meta-heuristic algorithms, or a combination of both (Nahhas et al., 2021).

Authors (Deepika & Dhanya, 2023) proposed a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm for the efficient selection of destinations in the Project Management (PM) phase. The method was initialized by providing the following inputs: the list of available PMs, the set of VMs to be migrated, the population size of the particles, the number of migrations (, the maximum number of repetitions, and other relevant parameters. Each Project Manager (PM) in the system was symbolically represented by a deploying solution including particles. The particles in this context indicate the dimensions of a particle, which are quantified by the number of relocated Virtual Machines (VMs). The fitness function determines the quality or effectiveness of the given problem. Hence, the ranking of each particle was contingent upon the fitness function's value. Based on the given information, particles continuously update their velocity and position in each iteration until they reach their personal best (best) and global best (best) values.

Authors (Justafort et al., 2019) presented a hybrid algorithm, namely ITS GCBF which made use of the Iterated Local Search (Wilson, 2023) algorithm to initiate the search process by selecting an initial solution and thereafter traverse the search space to identify the optimal configuration. The process begins by generating a solution utilizing a perturbation operator throughout each iteration, intending to achieve a new optimal solution through the utilization of a Local Search (LS) operator. The acceptance criterion in question is utilized to assess whether the optimal solution should be retained or discarded. The TS heuristic employs a Tabu list that retains a record of recent motions, preventing their repetition for a certain number of iterations (Tlili & Krichen, 2023). This mechanism effectively mitigates the occurrence of cycles and local optima. Nevertheless, the tabu status of a move is superseded if the ensuing solution surpasses the present optimal solution. The search ceases when all possible changes are considered forbidden, or when the current optimal solution remains unchanged for a specified number of iterations, denoted as Km. Enhanced memory techniques are frequently employed to address more challenging problem-solving tasks. To optimize outcomes, we suggest the utilization of a hybrid algorithm that incorporates Tabu Search (Tseng et al., 2018) as the Local Search (LS) operator within the Iterated Local Search (Wilson, 2023) heuristic.

State-of-the-art Comparison Parameters for Metaheuristic Algorithms Research Gaps and Discussion

While PSOs are simple to implement, reliable, fast to converge, computationally efficient, and problem-solving. These are the disadvantages of PSO. For example, difficult-to-define starting design parameters, scattering issues, premature convergence, and optimization in complex situations. (Mittal et al., 2021). The problem of multimodal optimization was addressed by (Wang, 2017), who offered a solution. Because of the integral arbitrariness of PSO, PSO is prone to dropping into local minima. Using the adaptive parameter control technique in multimodal situations improves PSO performance. It should be noted that the PSO's control parameters have a significant impact on performance. As a result, the dependence on the parameters may be reduced by the application of adaptive technology (Mittal et al., 2021). In addition, in comparison to the standalone PSO algorithm, the hybrid PSO or modified PSO design, which is set by the application, is preferable and provides the best possible performance (Mittal et al., 2021).

By definition, ACO algorithms are highly distributed algorithms in which a group of ants is responsible for independently creating a solution. Moreover, MOACOs offer excellent hybridization potential with other metaheuristics, like particle swarm optimization and genetic algorithms, in addition to local search engines. Over the next few years, it's anticipated that these hybrids will spread more widely (Falcón-Cardona et al., 2020). Finding a solution that offers a superior compromise among numerous other purposes is also necessary to address challenges with competing and varied aims. ACO algorithms are successfully applied in a variety of technological domains. As a result, ACO has effectively contributed to structural damage monitoring and digital picture processing. Also, ACO has attracted a lot of attention for its work in resolving economic dispatch challenges. Researchers are also investigating ACO's potential for scheduling, routing, and data clustering issues (Osaba & Yang).

The Cuckoo Search algorithm has piqued the interest of researchers due to its promising efficiency in real-world applications and ability to solve a wide range of optimization problems. According to the rapidly expanding literature, the cuckoo search algorithm is a very recent, active, and hot research field in the area of optimization such as Data fusion in wireless sensor networks, Engineering optimization problems, Neural network training, Manufacturing scheduling, and NP-hard combinatorial optimization problems, among others (Wadhwa & Verma, 2014b). Cuckoo search can find the desired solutions to many continuous optimization problems very efficiently. However, when appropriate solutions for other optimization problems cannot be found, some difficulties may arise. This is under the so-called NoFree-Lunch theorem. To get around this theorem, optimization algorithms for solving a specific set of problems have been hybridized. Cuckoo search has been hybridized with other optimization algorithms, machine learning techniques, heuristics, and so on. Hybridization can occur in almost every aspect of the cuckoo search (Xiao et al., 2022). In the meanwhile, this algorithm has issues with flexibility and acquiring the optimal search results, and it has a limited capacity to address difficult problems. The focus of future research should be on figuring out how to investigate novel approaches and techniques for enhancing the performance of high-coupling functions between variables (Wang, 2018).

Table 3. Comparison Parameters for Metaheuristic Algorithms

Author	Objective	Parameters	Results
(Sonmez, 2018)	objectively analyze various algorithms under identical conditions and choose the most efficient algorithm namely FA, GWO, PSO, ABC, GSA, GA, Jaya, and ACO.	efficiency and robustness	ACO, ABC, GWO, and Jaya outperformed GA, PSO, GSA, and FA. PSO, GSA, and FA had low DLG convergence. The PSO, GSA, and FA algorithms had poor convergence.
(Kaleka et al., 2020)	effective metaheuristic algorithm among the well-known ones namely PSO, MFO, SHO, GSA, WOA, GWO, ACO, and BA	Accuracy in exploration and exploitation strategies	SHO is superior to the other algorithms
(Ezugwu et al., 2020)	Compare and evaluate the results of some of these optimization algorithms namely IWO, GA, SOS, BA, DE, CS, FA, PSO, ACO, ABC, FPA and BeeA.	microscopic behaviour and computational capabilities	success ratios of the ACO, PSO, CS, GA, SOS, and DE, are better than FPA, FA, ABC, IWO, BA, and BeeA.
(Schellenberg et al., 2020)	Compare optimization effectiveness	run-time, accuracy, and reliability	PSO outperforms GA because of lower optimization error, shorter run-time, and higher dependability.
(Rajendran et al., 2022)	comparison study of six newly proposed metaheuristic algorithms, namely ALO, GWO, AOA, DA, SSA and WOA	convergence, processing difficulty, and statistical significance	GWO also showed fast convergence and SSA observed slightly better convergence than its counterparts.
(Zlobinsky et al., 2022)	Comparison study of SA, PSO, GA, and DE concerning Wireless Mesh Networks (WMN)	Best resultant	PSO, GA, and DE, three population-based algorithms, all successfully solve this problem. However, DE outperforms the others.
(Agushaka & Ezugwu, 2022)	Review of bat algorithm Grey Wolf Optimizer (GWO), (BA), and butterfly optimization algorithm (BOA)	The success of initialization schemes	Unlike GWO and BOA, BA is more sensitive to initialization schemes.
(Hosseini Shirvani, 2023)	Advanced MOD-JAYA	VMP process and its objective functions	Compared with other underlying algorithms, MOD-JAYA outperforms them in terms of looking at objective functions in the VMP process
(Vijaya & Srinivasan, 2024)	hybrid of the Sine Cosine Algorithm (Scarpiniti et al.) and Ant Colony Optimization (León-Aldaco et al.) algorithm and for efficient VMP (ACOSCA)	Optimization of energy and resource usage	ACO and SCA show a reduction in energy consumption, as well it exhibiting a reduction in resource wastage compared with other schemes

CONCLUSION AND FUTURE WORK

The matter of the carbon footprint's impact on data centres in the future is a multifaceted and indeterminate concern that necessitates collaborative efforts from several entities, including governments, enterprises, civil society, academics, and consumers. Through collaborative efforts aimed at designing and executing strategies to mitigate the ecological ramifications of data centres while concurrently optimizing their societal and economic advantages, we can guarantee that data centres remain a catalyst for positive change on a global scale.

Gaps identified from the review for future work, researchers also need to consider the exact methods that are being encouraged to be applied in energy optimization and reduction of carbon footprint. The ensemble of two or more metaheuristics, which combines the strengths of two or more algorithms into a single, more effective one is also encouraged. The large number of SI algorithms in the literature should be our first stop. Despite having many high-performing and reputable techniques, a portion of the community still searches the natural world for new biological phenomena to mimic. Recent works like and present algorithms based on butterfly behaviour and the Spanish soccer style, respectively, as metaphors for new metaheuristics. This continuous development of novel solvers adds to an already overcrowded literature by adding methods that do not advance the community. This trend increases critical scepticism. Several influential works have raised this issue, questioning the value of these novel approaches, which seem similar to others. This study invites scholars to consider the challenge of stopping technique development. Instead, we encourage the related community to elaborate on the adaptation of already existing well-known methods to a more demanding optimization problem.

Big data and machine learning techniques have the potential to contribute to the future optimization of energy grid operations and the reduction of carbon emissions by identifying and utilizing previously unexplored sources of flexibility. It is evident from this research that many authors have not focused on these approaches. This optimization can involve the redistribution of energy loads to periods and locations characterized by a greater proportion of carbon-free energy sources, such as wind and solar power. Load shifting enables the grid to more swiftly migrate towards greater proportions of carbon-free energy sources, while concurrently yielding reductions in operational expenses.

Also, future work is to come up with regulatory and policy frameworks that have the potential to provide incentives or impose mandates for the reduction of carbon emissions from data centres. Various frameworks can be employed to address environmental concerns, such as the implementation of carbon taxes or pricing mechanisms, the establishment of emission regulations or ceilings, the provision of subsidies or incentives to promote environmentally friendly solutions, and the enforcement of reporting or disclosure obligations.

Another prospect is to implementation of low-carbon technologies and practices, including but not limited to renewable energy sources, energy efficiency measures, circular economy models, and carbon capture and storage, which has gained significant attention in recent years. The implementation of various technologies and practices has the potential to mitigate the emissions associated with the manufacture, utilization, and disposal of information and communication technology devices and services.

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DECLARATIONS

Conflict of Interest

No conflict of interest in this study.

Informed Consent

Not applicable

Ethics Approval.

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