Sustainable Cloud Computing Realization for Different Applications: A Manifesto

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Abstract In cloud computing, an application design plays an important role and the efficient structure of an application can increase the energy-efficiency and sustainability of cloud datacenters. To make the infrastructure eco-friendly, energy-efficient and sustainable, there is a need for innovative applications. In this chapter, we comprehensively analyze the challenges in sustainable cloud computing and review the current developments for different applications. We propose a taxonomy of application management for sustainable cloud computing and identified research challenges. We also map the existing related studies to the taxonomy in order to identify current search gaps in the area of application management for sustainable cloud computing. Furthermore, we propose open research challenges for sustainable cloud computing based on the observations.

Keywords Cloud computing · Sustainable computing · Cloud application Sustainability · Energy efficiency

1 Introduction

Cloud resources are generally not only shared by a number of cloud users but are also reallocated dynamically based on the changing demand of cloud users. Sustainable use of the computing resources is required to improve the energy-efficiency of cloud datacenters [1]. To satisfy the future demand of application users, cloud computing needs an advanced sustainability theory for efficient management of resources. The technologies with green cloud computing are required for effective management of

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S. Patnaik et al. (eds.), *Digital Business*, Lecture Notes on Data Engineering and Communications Technologies 21, https://doi.org/10.1007/978-3-319-93940-7_4

all the resources (including cooling systems, networks, memory, storage and servers) in a holistic manner [2]. Presently, cloud computing paradigm supports an extensive variety of applications, but the usage of cloud services is growing swiftly with the current development of the Internet of Things (IoT) based applications. To fulfill the dynamic requirements of user applications, the next generation of cloud computing should be sustainable and energy-efficient. Currently, service providers are facing problems to ensure the sustainability of their cloud services [3]. Moreover, the sustainability of cloud services is also affected by usage of the large number of Cloud DataCenters (CDCs) to fulfill the demand of cloud users.

The various types of applications are executing on cloud infrastructure such as data-intensive or compute-intensive. There is a need to execute the applications in a concurrent manner to improve the performance of cloud computing systems [4]. Initially, Quality of Service (QoS) parameters for each cloud application is essential to be recognized based on the user requirements for provisioning of resources [5]. To improve the energy efficiency and sustainability of cloud datacenters, effective application modeling approach is used to design the cloud application [6, 7]. Green Information and Communications Technology (ICT)-based innovative applications are required to make the environment eco-friendly and sustainable infrastructure.

The rest of the chapter is organized as follows. In Sect. 2, we present the architecture for sustainable cloud computing for application management. After that, we discuss the existing related studies in Sect. 3. Based on existing research work, we propose a taxonomy of application management for sustainable cloud computing and map the existing research works to the proposed taxonomy in Sect. 4. In Sect. 5, we analyze research gaps and present some promising directions towards future research in this area. Finally, we summarize the findings and conclude the chapter in Sect. 6.

2 Sustainable Cloud Computing: Architecture

Figure 1 shows the layered architecture for sustainable cloud computing, which provides a holistic management of cloud computing resources (cooling systems, networks, memory, storage and servers), to make more sustainable and energy-efficient cloud services. There are three main services in cloud computing: Infrastructure as a Service (IaaS), Platform as a Service(PaaS) and Software as a Service (SaaS). An application manager is deployed at SaaS layer to manage the user applications such as smart home, ICT, healthcare, wearable devices, agriculture, aircraft, astronomy, education, artificial intelligence etc. At PaaS layer, Service manager controls the important aspects of the system. *IT device manager* manages all the devices attached to cloud datacenter. *Application model* defines the type of application for effective scheduling of different applications. *Application Scheduler* manages the user applications from the application model, finds the QoS requirements for each application for their effective execution and transfers the information about the quality of service of an application to the *Resource/VM manager*. *Remote CDC manager* handles the migration of VMs and workloads between local and remote cloud datacenters

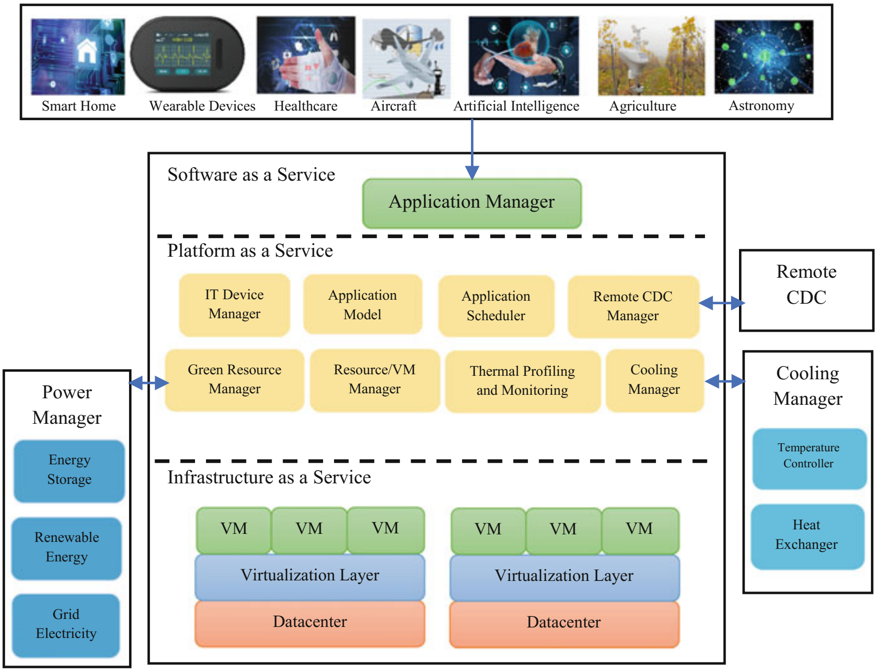

Fig. 1 Architecture for sustainable cloud computing

for effective utilization of energy. *Resource/VM manager* uses physical or virtual machines for scheduling of provisioned resources and executes the workloads based on their QoS requirements. *Green resource manager* manages the electricity coming from power manager and it prefers renewable energy as compared to grid electricity to enable sustainable cloud environment. It also manages the energy consumption of cloud datacenters to ensure sustainability of cloud services. The thermal sensors are used to monitor the value of temperature and *Thermal profiling and monitoring* technique analyze the variations of the temperature of the cloud datacenter. The *Cooling manager* controls the temperature of the cloud datacenter at the infrastructure level.

IaaS layer contains the details about virtual and physical machines of cloud datacenters. For an efficient execution of workloads, migrations of Virtual Machine (VM) is performed at virtualization layer for load balancing. The variation of the temperature of different VMs running at various cores is monitored proactively by the temperature-aware scheduler. The Cooling manager is deployed to maintain the required temperature to ensure the smooth functioning of computing resources of a cloud datacentre. If the temperature of CDC is more than its threshold value, then thermal alerts will be generated, and *Heat Exchanger* takes a required action to control the temperature of CDC with minimal effect on its performance. Further, the temperature is controlled by District heating management using water economizer, outside air economizer and chiller plant. Moreover, renewable energy resources and fossil fuels (grid electricity) generates power, which is controlled by Power Manager. The renewable energy is highly preferred instead of grid energy, which helps to enable energy-efficient and sustainable cloud environment. Further, grid energy can be used to execute deadline-oriented workloads, which improves the reliability of cloud services. Generally, solar and wind are two main sources of renewable energy and this energy is stored using batteries. The thermal sensor is used to monitor the value of temperature to generate an alert if the temperature is more than its value of threshold and pass the message to the heat controller for further action. Remote CDC is a cloud datacenter, which is located at a different place. VMs and workloads can be migrated to a remote CDC to balance the load effectively.

3 State-of-the-Art: Application Management

Application management plays a vital role in improving the performance of cloud computing systems. There are different types of cloud applications which need to be managed effectively from application modeling to its execution. An application should follow an efficient modeling approach during the design of an application. Further, green ICT-based innovative applications are required to make the infrastructure more sustainable. This section discusses the existing related studies in sustainable cloud computing for application management. Hazen et al. [8] analyzed supply chain functions' sustainability for big data analytics and identifies the factors affecting the performance of economic measures to improve data-driven process. They suggested that business people can use data analytics tools to improve the operational and strategic capabilities of the business. Furthermore, this research work analyzed the effect of data analytics on the sustainability of supply chain functions. Bifulco et al. [9] explored and analyzed the importance of ICT-based smart sustainable cities to improve environmental conditions while delivering the services with minimum consumption of energy. Further, Consumption Based Lifecycle (CBL) is presented to calculate the amount of consumption of power for daily household activities. Moreover, Dynamic Voltage and Frequency Scaling (DVFS) technique-based energy management mechanism is recommended to design a smart sustainable city, which can improve energy efficiency during the execution of ICT based cloud applications.

Rehman et al. [10] developed a Big Data Based Business (BDBB) model to manage the whole cloud applications using sustainability-aware approach to reduce the impact of carbon footprints on the environment. BDBB model manages the data by providing the following advantages: (1) improving resource utilization, which reduces cost, (2) establishing trust between provider and user and (3) improving data security and privacy preservation during data sharing. Cottrill and Derrible [11] recommended that big data can be used to develop sustainability indicators for transporting applications to create more efficient and sustainable transport system, which may also improve the GPS to trace the exact location of traffic congestion. Yekini et al. [12] introduced a new way to provide technical and vocational education using an autonomic cloud computing-based system, which delivers education resources to staff and student.

Maksimovic [13] developed an IoT based energy efficient model (Green-IoT), which uses big data analytics to develop more sustainable, smarter and secure cities. Further, energy-efficient IoT devices are considered for the network to assess the knowledge, which is used to deliver more sustainable services by making effective decisions during execution of IoT based applications. Bradley et al. [14] developed a cost-effective IoT based Parallel Design (IoT-PD) model for an efficient management of big data for cloud applications. Further, IoT-PD model generates the sustainable value using machine learning method to reduce its impact on the environment, which improves energy efficiency and sustainability of cloud services. Moreover, Perera and Zaslavsky [15] suggested utilizing energy-efficient IoT devices to increase the sustainability of services and developed a Trading-Based Value Creation (TBVC) model for effective utilization of IoT devices to execute real-time applications. Zuo et al. [16] proposed an IoT based Energy Efficient (IoT-EE) model to estimate the power consumption by cloud datacenters to execute user's workloads and analyze the energy consumption. Further, an objective function is developed to assess the delivering cloud service and IoT-EE model can be used in industry for designing and making of a product.

Bossche et al. [17] presented a Data Mining Based Model (DMBM) for text mining application, which uses unstructured data to extract useful information by removing extra information. Further, DMBM forms sustainable clusters using available resources efficiently. Cappiello et al. [18] developed a Green Computing Based Model (GCBM) to develop an application with lesser carbon emissions and maximum energy efficiency. Further, the reliability of a service is improved by ranking the application components based on their importance. Moreover, this research work also suggests two ways to choose a driven site for CO_2: (1) based on the availability of resources and CO_2 emissions and (2) based on the possible delay time. One limitation of this research work is that, authors did not suggest any action such as high cost associated to selected locations. Xia et al. [19] developed a Semantic Information services Architecture (SIA) for management of cloud services for matchmaking, retrieval and advertisement for electrical and electronic equipment. Further, the lifecycle of cloud providers is described using an ontology-based technique to analyze sustainability factors related to the semantic applications. Zgheib et al. [20] listed the advantages of IoT applications while delivering healthcare as a cloud service and developed a model to manage healthcare applications efficiently using message-oriented middleware. Further, exchanging of data is performed between different IoT devices using semantic web ontology language (OWL) messages. Gupta et al. [21] developed an IoT based Security-Aware Framework (IoT-SAF) to design sustainable and secure healthcare centres by analyzing different security aspects of IoT applications. The value of different parameters of health are managed using embedded sensors of the equipment and the gathered information is transferred to centralized cloud datacenter. Further, secure and faster data transmission in IoT-SAF is provided using XML web-based services.

NoviFlow [22] proposed a Green-Software Defined Network (G-SDN) model to make network infrastructure efficient and sustainable by offering sustainable solutions to reduce carbon emissions. Further, G-SDN model improves economic incentives by increasing energy efficiency of cloud datacenters. NoviFlow [22] identified that existing models are focusing on QoS and cost to provide energy-efficient cloud services. Pesch et al. [23] developed a Thermal-Aware Scheduling (TAS) technique for energy-efficient management of cloud resources to execute user applications, which improves the sustainability and energy efficiency of cloud datacenters. Experimental results show that TAS reduces the consumption of energy up to 40%. Chen et al. [24] presented a Cloud and Big Data (CBD) based model called *Smart Clothing* to use wearable devices to monitor the health status of patients. Experimental results show that CBD works efficiently for the long duration as compared to existing models [22, 23]. Waga and Rabah [25] proposed a sustainable Cloud-Based Framework (CBF) to manage agriculture data such as rainfall, wind speed and temperature to improve the use of climate and land in an efficient manner, which helps farmers to produce a profitable crop.

For desktop resource virtualization, Park et al. [26] proposed a Cloud-Based Clustering Simulator (CBCS) to choose the cluster for sustainable and energy-efficient cloud services. Based on network infrastructure and execution time, CBCS utilizes resources effectively without considering other resources such as processor, memory and storage. To improve the resource utilization and reduce the product-service cost for industrial product service system, Ding et al. [27] developed the Sustainability-Aware Resource Management (SARM) framework. Further, SARM helps to increase the satisfaction of users. Gmach et al. [28] presented a Power Profiling Technique (PPT) for CDCs, which increases the energy-efficiency and manages to decrease the carbon emissions and water consumption. Further, PPT analyzed the effect of demand and supply of energy on the environment. Moreover, PPT executes the workloads by fulfilling its QoS requirements while delivering the sustainable and energy-efficient cloud service.

Islam et al. [29] proposed a cloud-based Water-Aware Workload Scheduling (WAWS) framework to improve the water efficiency for cooling cloud datacenters during execution of cloud workloads. Further, water consumption is optimized by exploiting the spatio-temporal varieties of water efficiency. Dabbagh et al. [30] proposed an Energy-Efficient Technique (EET), which decreases the monthly expenditures of CDCs by postponing the execution of non-urgent workloads, which also helps urgent-workloads to achieve their deadline. Moreover, the control policy for prediction of demands of computing resources (storage, power memory etc.) of CDCs is designed for incoming requests. Further, EET is validated by using real traces of a Google CDCs. Garg et al. [31] developed an Environment Conscious Workload Scheduling (ECWS) technique for execution of High Performance Computing (HPC) applications on resources to improve the sustainability of cloud datacenters. Cheng et al. [32] developed Workload Placement and Migration Framework (WPMF) to improve throughput and sustainability of cloud datacenter for efficient execution of cloud workloads. WPMF executes transactional workloads on available resources and the workloads are migrated to different datacenters with the maximum value of energy efficiency.

Chen et al. [33] developed renewable energy sources based an Energy-Efficient Workload Management (EEWM) technique for sustainable cloud datacenter. Moreover, the temperature of CDC is controlled in EEWM using spatio-temporal diversity-based cooling facilities. Sehgal et al. [34] developed a smart human security framework based on IoT and Fog Computing (IoT-FC), which protects humans form an accident using the concept of wearable and pervasive computing. The secure communication between fog layer and IoT devices is managed by the cloud layer. Further, at fog and cloud level, the data is protected from external attacks. Khosravi and Buyya [35] proposed a Gaussian Mixture model based Short-term Prediction (GMSP) model to predict the renewable energy level to run datacenters and helps to take decisions for migration of VMs from one datacenter site to another. Further, GMSP can also perform online VM migration and experimental results show that GMSP can predict up to 15 min ahead. Desthieux et al. [36] proposed a Cloud-based Decision Support System (CDSS), which has high computing performance to control three-dimensional digital urban data that aids to provide an environmental analysis. Further, an analysis module of CDSS improves decision-making process to assess solar energy potential for installing new solar projects.

Table 1 describes the summary of these related techniques and their comparison based on the focus of study along with open research issues.

4 Taxonomy of Application Management for Sustainable Cloud Computing

Application management plays an important role to improve the sustainability and energy-efficiency of cloud services. The components of the application management taxonomy are: (i) QoS parameter, (ii) application parameters, (iii) application scheduling, (iv) application category, (v) application domain, (vi) resource administration, (vii) coordination and (viii) application model as shown in Fig. 2. Table 2 shows the comparison of existing techniques based on the proposed taxonomy of application management.

4.1 QoS Parameter

There are different QoS requirements for different user applications. Literature reported that three different types of QoS parameters for sustainable computing [2, 41, 42]: (i) cost related (utility and energy), (ii) time related (response time, throughput, availability and delay or latency) and (iii) others (correctness, easiness, resource utilization, privacy, security, reliability, robustness or scalability and inter-

Table 1 Comparison of existing techniques and open research challenges

Year	Technique	Focus of study	Open issues
2018	GMSP [35]	Prediction of level of renewable energy	Due to overloading of cloud resources, a huge number of workloads are waiting for their execution
	CDSS [36]	Solar energy potential management	The service delay is increasing by switching of resources between low and high scaling modes
2017	IoT-PD [14]	IoT devices	Secure communication is required to exchange information
	TAS [23]	Energy utilization	Heterogeneous workloads are not considered
	WAWS [29]	Water efficiency	Need to improve reliability of applications
	EET [30]	Storage efficiency	Over-utilization of resources affects throughput
	SARM [27]	Industrial product service	The response time is increased by switching of resources between low and high scaling modes
2016	IoT-SAF [21]	Web service security	The secure communication of IoT devices is required
	CBL [9]	ICT based smart cities	To improve energy efficiency, power is to be managed automatically
	CBD [24]	Smart clothing	Execution time is more, which reduces customer satisfaction
	EEWM [33]	Cooling management	The manipulation of supply voltage can save energy consumption by reducing the processor frequency
	BDBB [10]	Server utilization	Energy utilization is lesser, which leads to wastage of energy
2015	SIA [19]	Web ontology language (OWL)	There is need to improve retrieval speed in SIA
	IoT-FC [34]	Wearable and pervasive computing	The reliability of the storage component is affected by putting servers in sleeping mode or turning on/off
2014	TBVC [15]	Trading based value	The large consumption of energy by IoT devices increases carbon footprints
	GCBM [18]	CO_2 emissions	Under-utilization of resources increases cost of CDC
	CBF [25]	Agriculture	Energy consumption is more, which increases carbon footprints
	CBCS [26]	Desktop resource virtualization	The workload execution affects the resource utilization
	WPMF [32]	Heterogenous workloads	Due to speed gap between processor and main memory, a huge amount of clock speed is lost while waiting for the incoming data

(continued)

Table 1 (continued)

Year	Technique	Focus of study	Open issues
2013	DMBM [17]	Text mining	Response time is larger, which reduces customer satisfaction
2012	G-SDN [22]	Software defined network	Underloading of resources affects resource utilization
2011	ECWS [31]	HPC applications	Reserve resources are in advance increases cost
2010	PPT [28]	Greenhouse gas emissions	SLA violation can be reduced by using autonomic resource management technique

operability). "*Energy* is the amount of electricity consumed by a resource or resource set to finish the application's execution". A *Utility* is the effectiveness of an application while using practically after the development like banking application has high utility. *Response time* is defined as the amount of time consumed by a specific application to respond with the desired output. "*Throughput* is the ratio of the total number of tasks of an application to the amount of time required to execute the tasks". *Availability* is the amount of time (hours) a specific application will be available for use per day. *Delay or Latency* is a defined as a delay before the transfer of user request for processing. *Correctness* is defined as the degree to which the cloud service will be provided accurately to the cloud customers. *Easiness* is defined as the amount of efforts are required to use a specific application to complete a task. "*Resource Utilization* is a ratio of an execution time of a workload executed on a particular resource to the total uptime of that resource". *Privacy* is a QoS parameter through which user and provider can store their information privately using authorization and authentication.

Security is the capability of the computing system to protect from malicious attacks. *Reliability* is the capability of an application to sustain and produce correct results in case of occurrence of faults such as network, hardware or software related faults. *Robustness or Scalability* is the maximum number of users, which can access the application without degradation of performance. *Interoperability* is the degree to which an application can be ported to other platforms. Other QoS requirements of cloud computing systems can be network bandwidth etc.

4.2 Application Parameters

There are different types of application parameter, which can help to measure the status of an application [43, 44]. There are four main types of application parameters: (a) budget, (b) deadline, (c) capacity and (d) performance. *Budget* is the amount of cost that user wants to spend for the execution of their task and measured in dollars ($). *Deadline* is the maximum time limit allowed to execute the user application and measured in seconds. *Capacity* is defined as the capability of an application to

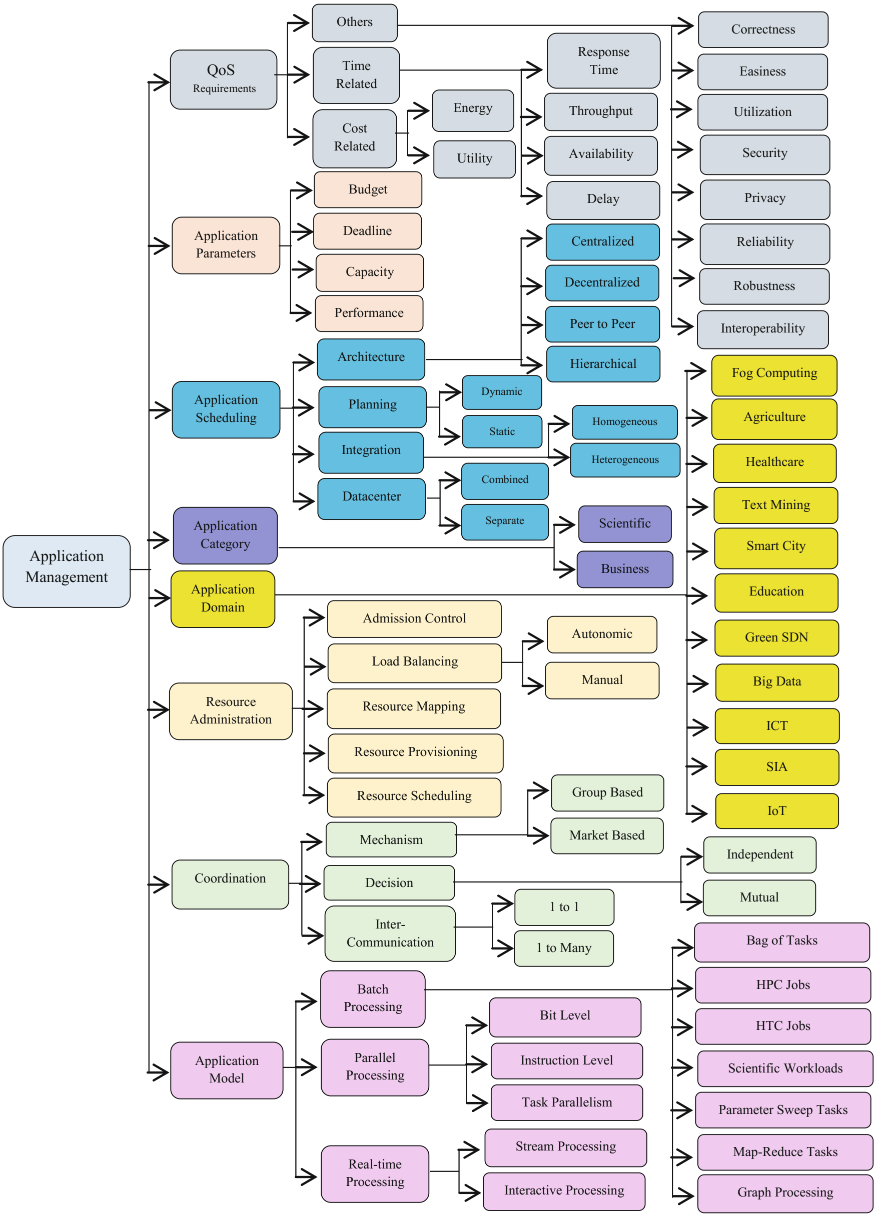

Fig. 2 Taxonomy of application management for sustainable cloud computing

execute user tasks using available resources such as power infrastructure, IT devices etc. *Performance* is a parameter, which is used to measure the status of an application during an unexpected spike in traffic.

4.3 Application Scheduling

There are four components of an application scheduling as studied from literature [1, 2, 45, 46]: (a) architecture, (b) planning, (c) integration and (d) datacenter. The *architecture* of cloud computing system is a vital component and four different types of architectures are identified from literature: hierarchical, peer to peer, decentralized and centralized. *Peer-to-peer* is networking architecture in which each cloud node, has the same capabilities and responsibilities to execute user task. There is two levels of schedulers in the *hierarchical* architecture: lower and higher level. The lower-level scheduler assigns resources to every small task, which is controlled by a higher-level scheduler to reduce the complexity of resource allocation. There is no mutual coordination in *decentralized* architectures and it executes the tasks by allocating resources independently. In *centralized* architectures, all the tasks that are needed to be executed are managed by a central controller and scheduled resources are used to execute these tasks using coordination mechanism. *Planning* of a cloud application is done using two types of resource scheduling: static and dynamic. In *static* resource scheduling, a required resource is mapped to user workload based on their QoS requirements, while *dynamic* resource scheduling maps and executes the user workloads using provisioned resources. To find out the result of different execution units, an *integration* function is used by the scheduler, which can be *combined* or *separate*. The literature reported two different types of *datacenters*: heterogeneous and homogeneous. A CDC with the same configuration of computing resources such as processors, storage, networking and operating systems to process user applications is called a *homogenous* datacenter, while a CDC is a combination of different configurations of computing resources is called a *heterogeneous* datacenter.

4.4 Application Category

The cloud computing paradigm is a very effective platform, which can handle the increasing complexity of user applications. As studied form literature [3, 39, 40], two types of user applications are identified: scientific and business. The *Business* application is a platform, which enables the execution of business functions. For example: banking systems and online shopping websites. *Scientific* applications contain the real-world activities, which needs high computing capacity to execute user requests. For example: oil exploration, aircraft design and fuel efficiency, weather prediction and climate modeling, flight control system etc.

Table 2 Review of state-of-the-art based on taxonomy

Technique	Application domain	Application category	QoS parameter	Application scheduling				Application parameter	Resource administration	Coordination			Application model		
				Architecture	Planning	Integration	Datacenter			Mechanism	Decision	Inter communication	Batch processing	Realtime processing	Parallel processing
GMSP [35]	Smart city	Business	Energy	Centralized	Dynamic	Separate	Homogeneous	Capacity	Resource mapping	Group based	Independent	1 to many	Map-Reduce tasks	Bit level	Stream processing
CDSS [36]	ICT	Scientific	Cost	Peer to peer	Dynamic	Combined	Heterogenous	Performance	Resource mapping	Market based	Independent	1 to 1	Bag of tasks	Bit level	Interactive processing
IoT-PD [14]	IoT	Business	Time	Centralized	Static	Separate	Heterogenous	Deadline	Admission control	Group based	Mutual	1 to many	Map-Reduce Tasks	Task Parallelism	Interactive Processing
TAS [23]	Smart city	Scientific	Delay	Decentralized	Dynamic	Separate	Homogeneous	Deadline	Load balancing	Market based	Independent	1 to Many	HPC Jobs	Instruction Level	Stream Processing
WAWS [29]	Smart city	Business	Availability	Hierarchical	Static	Combined	Heterogenous	Capacity	Resource Selection	Group Based	Mutual	1 to 1	HTC Jobs	Bit Level	Interactive Processing
EET [30]	Big data	Business	Throughput	Hierarchical	Dynamic	Separate	Homogeneous	Performance	Admission Control	Market Based	Independent	1 to Many	Bag of Tasks	Instruction Level	Stream Processing
SARM [27]	Smart city	Scientific	Response time	Centralized	Static	Separate	Heterogenous	Deadline	Load Balancing	Group Based	Mutual	1 to 1	HTC Jobs	Bit Level	Interactive Processing
IoT-SAF [21]	Healthcare	Business	Interoperability	Peer to peer	Static	Combined	Homogeneous	Performance	Load Balancing	Group Based	Independent	1 to Many	HPC Jobs	Bit Level	Interactive Processing
CBL [9]	ICT	Scientific	Cost and robustness	Decentralized	Static	Combined	Heterogenous	Budget	Resource Selection	Market Based	Independent	1 to 1	Bag of Tasks	Task Parallelism	Interactive Processing
CBD [24]	Healthcare	Business	Time and reliability	Centralized	Dynamic	Separate	Homogeneous	Capacity	Resource Provisioning	Group Based	Mutual	1 to Many	Scientific Workloads	Instruction Level	Interactive Processing
EEWM [33]	ICT	Scientific	Energy and privacy	Peer to Peer	Dynamic	Combined	Heterogenous	Deadline	Resource Selection	Market Based	Independent	1 to Many	Scientific Workloads	Instruction Level	Stream Processing
BDBB [10]	Big data	Scientific	Security	Hierarchical	Dynamic	Combined	Homogeneous	Capacity	Load Balancing	Group Based	Independent	1 to 1	HPC Jobs	Instruction Level	Interactive Processing

(continued)

Table 2 (continued)

Technique	Application domain	Application category	QoS parameter	Application scheduling				Application parameter	Resource administration	Coordination			Application model		
				Architecture	Planning	Integration	Datacenter			Mechanism	Decision	Inter communication	Batch processing	Realtime processing	Parallel processing
SIA [19]	Semantic Service	Business	Resource utilization	Centralized	Static	Separate	Heterogenous	Performance	Resource Selection	Market Based	Mutual	1 to 1	Parameter Sweep Tasks	Task Parallelism	Interactive Processing
IoT-FC [34]	Fog computing	Scientific	Cost and easiness	Hierarchical	Static	Combined	Homogeneous	Budget	Admission Control	Group Based	Independent	1 to Many	Map-Reduce Tasks	Instruction Level	Interactive Processing
TBVC [15]	IoT	Business	Time and correctness	Hierarchical	Static	Separate	Heterogenous	Performance	Load Balancing	Group Based	Independent	1 to Many	Bag of Tasks	Task Parallelism	Stream Processing
GCBM [18]	Smart city	Scientific	Response time	Decentralized	Dynamic	Separate	Heterogenous	Budget	Load Balancing	Market Based	Mutual	1 to Many	Map-Reduce Tasks	Instruction Level	Interactive Processing
CBF [25]	Agriculture	Scientific	Availability	Decentralized	Dynamic	Combined	Homogeneous	Performance	Resource Selection	Group Based	Mutual	1 to 1	Map-Reduce Tasks	Bit Level	Interactive Processing
CBCS [26]	Big data	Business	Throughput	Peer to Peer	Static	Separate	Homogeneous	Performance	Load Balancing	Market Based	Mutual	1 to 1	Graph Processing	Bit Level	Stream Processing
WPMF [32]	Big data	Scientific	Cost	Centralized	Dynamic	Separate	Heterogenous	Budget	Resource Provisioning	Group Based	Independent	1 to Many	Map-Reduce Tasks	Instruction Level	Interactive Processing
DMBM [17]	Text mining	Business	Time	Hierarchical	Static	Combined	Heterogenous	Deadline	Resource Selection	Group Based	Mutual	1 to 1	Graph Processing	Task Parallelism	Interactive Processing
G-SDN [22]	Green-SDN	Scientific	Energy and utilization	Decentralized	Dynamic	Combined	Homogeneous	Capacity	Resource Provisioning	Market Based	Independent	1 to Many	HPC Jobs	Instruction Level	Stream Processing
ECWS [31]	Smart city	Business	Time and cost	Centralized	Static	Separate	Homogeneous	Performance	Resource Provisioning	Group Based	Mutual	1 to 1	HPC Jobs	Instruction Level	Interactive Processing
PPT [28]	ICT	Scientific	Energy and robustness	Peer to peer	Static	Combined	Heterogenous	Budget	Resource Selection	Market Based	Independent	1 to Many	Parameter Sweep Tasks	Bit Level	Interactive Processing

4.5 Application Domain

In order to satisfy different kinds of customers, the applications are created for an extensive range of domains to make cloud services more sustainable and to improve customer satisfaction [2, 37, 38]. To develop sustainable smart cities, *ICT based applications* are designed, which reduces energy consumption of cloud datacenters. The use of Internet-based smart devices is growing exponentially, and it is important to adopt *IoT based technology* for secure, fast and reliable communication, which delivers the sustainable cloud services. To improve the consistency of that knowledge among all the cloud users, *Semantic* web ontology language exchanges the information among smart devices, IoT devices etc. Cloud user can access the unstructured data and retrieve the required information using text mining-based cloud applications. Further, to improve the process of matchmaking and retrieval of data, applications are designed to provide *Semantic information services*. Moreover, *Fog computing*-based models such as driverless car and human security models are developed using IoT devices. For example, people can use wearable devices to protect themselves from any future accident, which improves the sustainability of IoT devices. To reduce the carbon emissions and improve the communication in terms of sustainability, *Green-Software Defined Network (G-SDN)* is designed, which improve the network lifetime of IoT devices. ICT based application and IoT devices are used in an integrated manner to design smart cities, which can control energy consumption and provide a way for effective use of resources in an efficient manner. Other important application domains of sustainable cloud computing are agriculture, education and healthcare. *Agriculture* applications aid to manage agriculture data such as rainfall, wind speed and temperature to improve the use of climate and land in an efficient manner, which helps farmers to produce a profitable crop. Students and staff can access available open education resources using *education*-based applications. Further, wearable devices can be used to measure the health status of patients using IoT based *healthcare* applications.

4.6 Resource Administration

Resource Administration consists of five main components [47, 48]: (1) load balancing, (2) admission control, (3) resource provisioning, (4) resource scheduling and (5) resource monitoring. *Load balancing* is a process to effectively distribute the workload over all the available resources to maintain the performance of a computing system and load balancing can be *autonomic* or *manual*. *Admission control* mechanism is used to ensure that sufficient resources are available to provide failover protection by reserving resources in advance. The process of identifying adequate resources from resource pool based on application requirement is called *Resource provisioning* [8], whereas mapping of provisioned resources through resource provisioning for application execution [10] is called *resource scheduling.* The main aim of effective resource management is to schedule the provisioned cloud resources for execution of an application, so that application can execute with maximum resource utilization [11]. *Resource monitoring* is a process to measure the value of QoS parameters during workload execution.

4.7 Coordination

Coordination is a process through which different applications can communicate to achieve a common goal [1, 41, 42] and three components of coordination are: (1) mechanism, (2) decision and (3) intercommunication protocol. In the cloud, there are two types of *mechanism*: market-based and group-based. In *market-based* mechanism, the concept of Service Level Agreement (SLA) based negotiation is used to deliver the resources to different applications. In *group-based* mechanism, resources are shared within the groups formed based on the same QoS requirements of an application. Literature reported that there are two different types of *decisions*: independent and mutual. Resource scheduler schedules the resources independently for workload execution in the *independent* decisions scheme without focusing on resource utilization. The concept of mutual coordination is used in the *mutual* decisions scheme, to make the coordination between high-level and low-level scheduler for execution of all the tasks of user application. The components of an application are interacting with each other using two types of intercommunication protocol: one to many and one to one. Based on negotiated SLA, one consumer is getting with one provider in *one to one* protocol, while one cloud provider offers service to more than one user in *one to many* intercommunication protocol.

4.8 Application Model

There are three types of *application models* as identified from literature [47, 48]: (1) real-time processing, (2) batch processing and (3) parallel processing. *Real-time processing* is a processing of data which requires continuous input, process and output of data and it processes data in a short span of time. For example: processing of data at radar systems and bank ATMs. There are two types of real-time processing: (1) stream processing and (2) interactive processing. *Stream processing* is a processing of small-sized data (in Kilobytes) generated continuously by thousands of data sources (geospatial services, social networks, mobile or web applications etc.), which typically send data records simultaneously. In *interactiveprocessing*, the workloads can be executed anytime but its execution of a workload must be finished before their desired deadline. *Batchprocessing* is a type of data processing (large batches of data) which is needed to run all time i.e. 24×7 like Internet services, delay torrent etc. to execute user workloads.

There are seven types of batch processing: (1) bag of tasks, (2) HPC jobs, (3) HTC jobs, (4) scientific workloads, (5) parameter sweep tasks, (6) map-reduce tasks and (7) graph processing. *Bag-of-tasks* refers to the jobs that are parallel among which there are no dependencies, for example: video coding and encoding. *High-Performance Computing (HPC) jobs* in which single computer is used to solve large problems in business, engineering or science such as advanced application programs, which need to be executed efficiently, reliably and quickly. *High-Throughput Computing (HTC) jobs* in which large number of computing resources are running to finish the execution of a computational task. In *scientific workloads*, real workload activities can be simulated like weather prediction, flight control system etc. which requires high processing capacity to process it. *Parameter sweep tasks* are identical in their nature and differ only by the specific parameters used to execute them. *Map-reduce tasks* split the input data-set into independent chunks and parallel way of execution, which is used to execute the mapped tasks. Further, the outputs of the maps are sorted and used as an input to the reduce tasks. *Graph processing* involves the process of analyzing, storing and processing graphs to produce effective outputs. *Parallel processing* is an operation in which job is divided into small independent parts and execute all simultaneously on different processing nodes to improve the speed of an application. There are three types of parallel processing: (1) bit-level, (2) instruction level and (3) task parallelism. *Bit-level* parallel processing divides the job into the number of bits for execution, while instruction level parallel processing executed different instructions of a specific job. In *task parallelism*, a large task is divided into little tasks and execute them parallelly.

5 Gap Analysis and Future Research Directions

Researchers have done a large amount of research work in the area of application management for sustainable cloud computing but there are some research issues still pending to address. Following are research gaps as identified from the literature [2–7, 37–49] as discussed in Sect. 3.

5.1 Application Modeling

The future cloud applications should be developed with three-tiered architectures, which has three different layers: (i) database, (ii) application processing and (iii) user interface. To improve the reliability, simplicity and performance of an application, the functionality of every tier must be independent to execute at heterogeneous resources. The components of applications should follow loosely coupled design to decrease dependency among them, so that application can be migrated from one CDC to another without degrading its efficiency of their execution. Furthermore, data security should be provided to protect a data of e-commerce applications from unauthorized users. The future application of cloud computing can be smart home, smart city, smart dust, smart lipstick etc.

5.2 Resource Management

Resource management is the organized method of scheduling of available resources to the required customer's workloads over the Internet. Applications should be executed by allocating virtual resources in optimized manner and workload should be executed with minimum cost and time. Effective resource management in the virtual environment can improve resource utilization and user satisfaction. There is a problem of under-provisioning and over-provisioning of resources in existing resource allocation techniques. To overcome this problem, a QoS-aware resource management technique is required for efficient execution of cloud applications.

5.3 Energy Efficiency

To provide a reliable cloud service, it is required to identify that how the occurrences of failures affect the energy efficiency of cloud computing system. Moreover, it is necessary to save the checkpoints with the minimum overhead after predicting an occurrence of the failure. Therefore, workloads or VMs can be migrated to more reliable servers, which can save the energy consumption and time. Further, consolidation of multiple independent instances (web service or email) of an application can improve the energy efficiency, which improves the sustainability and availability of cloud service.

5.4 Reliability and Fault Tolerance

The prominent cloud providers such as Google, Facebook, Amazon and Microsoft are providing highly available cloud computing services using thousands of servers, which consists of multiple resources such as processors, network cards, storage devices and disk drives. With the growing adoption of cloud, CDCs are rapidly expanding their sizes and increasing the complexity of the systems, which increases the resource failures. The failure can be SLA violation, data corruption and loss and premature termination of an application's execution, which can degrade the performance of cloud service and affect the business. For next-generation clouds to be reliable, there is a need to identify the failures (hardware, service, software or resource), their causes and manages them to improve their reliability. To solve this problem, a model and system is required that introduces replication of services and their coordination to enable reliable delivery of cloud services in a cost-efficient manner for an execution of cloud application.

5.5 Security and Privacy

Real cloud failure traces can be used to perform the empirical or statistical analysis about failures to test the performance in terms of the security of the system. Security during migration of virtual machines from one CDC to another is also a significant issue because a state of a VM can be hijacked during its migration. To solve this problem, there is a need for encrypted data transfer to stop user account hijacking, which can provide a secure communication between user and provider. To improve the sustainability and reliability of cloud service to next level, homomorphic encryption methods can be used to provide security against malicious attacks like denial of service, password crack, data leakage, DNS spoofing and eavesdropping. Further, it is required to understand and address the causes of security threats such as VM level attacks, authentication and authorization and network-attack surface for efficient detection and prevention from cyber-attacks. Moreover, data leakage prevention applications can be used to secure data, which also improves the sustainability and reliability of cloud-based applications.

5.6 Scalability

The unplanned downtime can violate the SLA and affects the business of cloud providers. To solve this problem, a cloud computing system should incorporate dynamic scalability to fulfill the changing demand of user applications without the violation of SLA, which helps to improve the sustainability of cloud services during peak load.

5.7 Latency

Virtualization overhead and resource contention are two main problems in computing systems, which increases the response time. A reliability-aware computing system can minimize the problems for real-time applications such as video broadcast and video conference, which can reduce latency while transferring data to improve the sustainability of computing systems.

5.8 Data Management

Computing systems are also facing a challenge of data synchronization because data is stored geographically, which overloads the cloud service. To solve this problem, rapid elasticity can be used to find the overloaded cloud service and it adds new instances to handle the execution of current applications. Further, there is a need for an efficient data backup to recover the data in case of server downtime.

5.9 Auditing

To maintain health stability of the cloud service, there is a need for periodic auditing by third parties, which can improve the sustainability, reliability and protection of computing system for future cloud-based applications.

5.10 New Technological Developments

Cloud computing paradigm utilizes the Internet to provide on-demand services to cloud users and emerged as a backbone of a modern economy. Recent technological developments such as the Internet of Things, fog computing, software-defined clouds, big data and smart city are creating new research areas for cloud computing. There is need of the re-evaluation of existing application models of cloud computing to address research issues such as energy efficiency, sustainability, privacy and reliability.

5.10.1 IoT and Big Data for Smart Cities

The emerging big data and Internet of Things (IoT) applications such as smart cities, healthcare services etc. are increasing, which needs fast data processing to improve the sustainability of computing systems. However, these applications are facing large delay and response time because computing systems need to transfer data to the cloud and then cloud to an application, which affect its performance. Fog computing is a solution to reduce the latency, in which cloud is extended to the edge of the network. IoT environment using fog-assisted cloud computing for processing of data to make smarter decisions in a permitted time period. The data collected from different IoT devices have a large variety and volume (also known as Big Data), which also needs fog servers with high processing power. As a result of regular capturing and collection of datasets, they grow with the velocity of 250 MB/min or more. The continuous exchange of data in IoT environments is using for efficient decision making and real-time analytics for smart cities.

5.10.2 Software Defined Clouds

Software Defined Network (SDN) based software defined clouds can be used to provide secure communication during the execution of a user applications. Transport Layer Security (TLS)/Secure Sockets Layer (SSL) encryption techniques can also be used to provide secure communications between the controller(s) and OpenFlow switches, the configuration is very complex, and many vendors do not provide support of TLS in their OpenFlow switches by default. SDN security is critical since threats can degrade the availability, performance and sustainability of the network.

5.10.3 Fog Computing

The Fog computing paradigm offers a virtualized intermediate layer to provide data, computation, storage, and networking services between cloud datacenters and end users. The megatrend of Internet of Things (IoT) based real-time applications such as health monitoring, disaster management and traffic management requires lesser response time and latency to process user tasks. Therefore, fog computing is a solution to improve performance, in which cloud is extended to the edge of the network. Further, following open issues and challenges are required to be addressed to realize the full potential of fog-based application management for sustainable cloud computing.

- *Trade-off between Security and Reliability*: It is very difficult to incorporate security protocols in fog computing due to its distributed environment. One of the main security issues is calling authentication at different levels of fog devices. Trusted execution environment and Public-Key Infrastructure based on authentication solutions can provide a security to fog computing. To reduce authentication cost, rogue devices can be detected using measurement-based methods. Reliability is one of the main issues since fog computing is comprises of large number of geographically distributed devices. Reliability protocols for sensor networks can be used in case of failure of a cloud application, service platform, network and individual sensors. Reading of sensors can be affected by noise; concept of redundancy can be used to solve the problem of information accuracy.
- *Trade-off between Resource Utilization and QoS*: Fog devices have additional compute and storage power, but it is not possible for these devices to provide the resource capacity of cloud. Therefore, efficient resource management technique is required to process the application requests in a timely manner. To solve this problem, resource usage of user application should be predicted accurately in advance which can utilize resources efficiently. Moreover, existing resource management techniques in fog computing considers execution time only. In addition; required technique needs to consider the basic features of cloud computing in order to optimize the important QoS parameters such as execution time, energy consumption and network usage.

- *Trade-off between Latency and Power Consumption*: Fog environment consist of large number of fog devices in a distributed manner and computation may be consuming more energy than centralized cloud environment, hence it is an important research issue. Existing research reported that fog devices are more capable to reduce latency as compared to cloud by experiencing a little larger energy consumption during the execution of cloud-based applications. In fog computing system, trade-off between delay and power consumption is an open research area.

6 Summary and Conclusions

In this chapter, the survey of recent developments in application management for sustainable cloud computing has been presented. We identified the focus of study of existing techniques and proposed open research challenges. Based on the identified important open issues and focus of study, a taxonomy of application management for sustainable cloud computing has also been presented. Our taxonomy categorizes and investigates the existing research works based on their techniques towards addressing the research challenges. Moreover, we proposed some promising research directions based on the analysis, that can be pursued in the future.

Acknowledgements One of the authors, Dr. Sukhpal Singh Gill [Post Doctorate Research Fellow], gratefully acknowledges the Cloud Computing and Distributed Systems (CLOUDS) Laboratory, School of Computing and Information Systems, The University of Melbourne, Australia, for awarding him the Fellowship to carry out this research work. We thank SaraKardani Moghaddam and ShashikantIlager for their comments on improving the chapter.

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