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Data center maintenance: applications and future research directions

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Abstract

Purpose – One of the most critical infrastructures is a data center (DC) because of it having many servers, computers and other equipment. DCs provide online services for various companies in the information technology (IT) industry. DC facilities should provide reliable online services while addressing the required quality and performance level considering maximum reliability and availability. The purpose of this study is to represent and classify the main findings in this area and to identify the main research gaps and shortcomings from the perspective of research.

Design/methodology/approach – This paper provides an organized and systematic literature review focusing on topics regarding the operation and maintenance (O&M) management of DCs.

Findings – Although there are several studies on O&M management systems for industrial systems and facilities, a limited number of studies with few methods and models have focused on DCs so far and these facilities require more attention. This paper identifies the issues and challenges for DC buildings and facilities and provides a conclusion of the findings to highlight the main research limitations for discovering new potential methods as future research opportunities.

Research limitations/implications – The paper has highlighted the main practical issues of DCs in terms of maintenance management. Several research works have been discussed specifically for DC's maintenance, which makes this paper a credible source for researchers, maintenance managers and companies involved in the area of DC. Because several of the reviewed literature were based on real case studies, decision-makers in the DC maintenance sector can take advantage of new research on maintenance scheduling to reduce the costs of maintenance.

Originality/value – The paper has presented a comprehensive list of frequent keywords in recent publications related to O&M management for DCs. It has provided a categorized list of publications based on by their topic, methodology and case study. Because this paper has discussed research works specifically for DC's maintenance, it is a credible source for researchers, maintenance managers and companies involved in the area of DCs.

Keywords Operations management, Information technology (IT), Maintenance management, Facilities management (FM), Data center (DC), Maintenance scheduling

Paper type Literature review

1. Introduction

A data center (DC) is a major infrastructure and facility which contains a high quantity of servers and computers to provide internet services for many companies in the world (such as Google, Amazon, etc.). The term "data center" may have different meanings from various points of view and there are also some other similar names such as data hall, data farm, data warehouse, computer room, server room, etc. which have been used by researchers and scholars. According to U.S. Environment Protection Agency (EPA), DC is a type of principle electronic equipment that is used for processing data (server devices), storing the data (storage equipment) and communications including networking tools and devices. DC

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requires special power conversion and backup equipment to preserve high-quality and reliable power system. The system maintains important environmental factors such as proper temperature and humidity for the Information and Communication Technology (ICT) equipment (Geng, 2015). The principal components and equipment located in DCs are computers, servers, cooling systems, storage devices and supply devices. Three main subsystems located in a general (traditional) DC are continuous power supply, air conditioning and network connectivity (Saha *et al.*, 2016).

Corresponding to different references, there have been various changes in the technology of DCs such as other technologies in the world. As there were computer rooms in the middle of the twentieth century, DC began to operate in those computer rooms as a shelter or house. Later, these computer housings became large and complex infrastructures. The ARC net is recognized as the first DC, placed in a special area. About 10,000 ARC net DCs were used globally by 1980s. From the beginning of the 1990 decade, as the usage of personal computers was increasing in the world, users had access to a network. Therefore, the real difference appeared and the mainframe which existed before was converted into places hosting many servers. These places were later named "data centers" (Carey *et al.*, 2017).

DCs are industrialized centers located worldwide and the number of them is growing because of high demands for several services. As specified by references and reports, the total number of DCs worldwide in 2017 was about 8.4 million. Based on the literature, there are about 8.6 million enterprise data centers operating globally. Also, the number of cloud data centers (which will be elaborated in the next pages) has been increased recently. Moreover, DC facilities have been combined and became hyperscale DCs. Therefore, because of the stated reasons, the total quantity of DCs has been decreased from 8.55 million in 2015 to about 8.4 million in 2017 but the demand for data storage and processing is rising. It is estimated that this number will reduce to 7.2 million until 2021 (Statista, 2017; Williams, 2018). According to statistics, the amount of data center storage consumed by big data worldwide will require about 124 exabytes of DC storage space globally until the end of 2018 and will grow up to 403 exabytes by 2021 (Cisco Systems, 2018b). In addition, in 2018, the storage capacity of DCs reached 1,450 exabytes in the world with 250 exabytes being consumed by collaboration activities and data. The storage capacity will increase up to near 2,500 exabytes by 2021 (Cisco Systems, 2018a).

Regarding the provided statistics related to DCs, there are several challenges and issues in managing DC facilities and their components. Especially, the amount of power being consumed by servers is noticeable. Concerning energy consumption, it should be noted that DCs use about 40 times energy than other standard buildings such as offices. Thus, energy management tools that have been used for regular office building could not be easily applied for DCs because the energy simulation of DCs is complicated. There are considerable differences in terms of energy loads and the structure of buildings between DCs and commercial buildings (Cho *et al.*, 2015). Research and studies have been performed on DC operations by scientists to effectively apply the DC operations management framework for reducing the staff workload. In addition, the other goal is increasing the work efficiency to bring maximum overall effectiveness for the DC operations management system (Bai and Geng, 2015). In terms of DC power and energy usage, the indicated numbers express high and increasing energy demands. The servers and DCs have used 61 billion kWh, costing $4.5bn in the year 2006 and it was expected to be doubled by the year 2011. Based on recent studies, one server with 300 W power has about $330 energy cost in a year (Guenter *et al.*, 2011). In addition, the total electricity consumption of DCs in the USA has reached 60 billion kWh per year in 2014 and will rise to 70 billion kWh per year until 2020. Fortunately, based on the presented numbers, responsiveness about infrastructure operations in DC has

increased and thus the efficiency has been improved, specifically in cloud DCs. Moreover, recently, the cloud DCs are designed to maximize the efficiency of the DC infrastructure. Generally, cloud DCs host around 10,000 servers for offering various services to be used by the applications (Saha *et al.*, 2016; Shehabi *et al.*, 2016).

DCs play an essential role in our fast-developing society as main information technology (IT) infrastructures. Because of the complexity of IT equipment placed in DCs, the reliability, availability and maintenance of its components require more attention. Based on recent studies, DCs should adjust themselves to the fast-developing industry. In addition, the operations and maintenance (O&M) management system should carefully be considered and formed based on the required standards to obtain a standard management system to meet DC's acceptable performance (Zhan and Zhang, 2014).

2. Literature review

In this paper, at first, review papers have been searched in the field of O&M management systems, generally. The purpose was to find previous similar literature reviews, published in the past five years, which have discussed these systems generally or for specific applications or systems in the industry. Based on findings, up to now, there are a few papers that have focused on various models and methods of O&M management. The most relevant review papers have been selected and discussed in the next paragraphs of this section. They present a wide range of studies about the maintenance and operations, their evolution and application in different systems. They have also discussed, classified and reviewed the applied methodologies.

Generally, the maintenance management process in any system, including DCs, could be classified into two main steps. First, the approach is determined, and then the strategy should be implemented in the system (Márquez, 2007). The latter phase consists of the following:

- maintenance planning for all assets in the system;
- maintenance scheduling;
- data collection to manage maintenance actions;
- maintenance assessment by having appropriate measurements;
- checking the improvement of maintenance tasks by conducting the required modifications; and
- analyzing any necessary modifications for re-designing any components in the system (Márquez, 2007).

Various models of maintenance management systems have been categorized by researchers to demonstrate the empirical evidence for using these models in real worldwide projects. They obtained a solution to improve the empirical evidence rates (EER) for maintenance. The scholars have searched for various maintenance management models in several articles and finally found 37 different models (Fraser *et al.*, 2015).

According to a literature review focusing on maintenance and facility management, while the warehouse's operational performance and logistics are influenced by facility management, there is a lack of research in this area to highlight the importance of facility management for logistics operations (Mangano and de Marco, 2014). In addition, other researchers have identified the main issues of maintenance operations by comparing them with the problems found in the manufacturing operations. A systematic approach is performed to classify the literature and to analyze them. Based on calculations, the

maintenance operations and manufacturing operations have similar problems such as not having top management support, not measuring the overall equipment effectiveness (OEE) and not presenting strategic planning and implementation. With regard to their discussions, both performance and productivity of machines should be considered for proper maintenance (Phogat *et al.*, 2017). Research on building's dynamic energy performance was reviewed to highlight the main developments of the major phases such as monitoring, diagnosing and retrofitting. The goal was to concentrate on the O&M phase, as a part of the diagnosing phase, and to review main advances for reducing the carbon emissions in this phase of the buildings. The operational rating system, which is a measurement tool for applying in the building's O&M, was discussed (Hong *et al.*, 2015). A comprehensive literature review is published in two parts concerning performance indicators for facilities O&M. In the first part (Lai and Man, 2018a), the most important performance indicators (about 70) are mapped and classified based on the phase-hierarchy (P-H) model. These indicators were defined and classified from the facility management (FM) perspective. It could be a useful source of various indicators which is essential in most types of buildings. In the second part, the key performance indicators (KPIs) are discussed with groups of O&M experts in the commercial buildings sector to obtain their comments and ideas for shortlisting the total performance indicators found in the first part. This shortlist of KPIs has the potential to be used by professionals of FM in commercial buildings. Also, the same approach for obtaining a shortlist of the important indicators could be applied to other building sectors (Lai and Man, 2018b). In the case of office buildings, extensive research based on interviews and surveys has been performed to develop an FM process model. This model includes essential parameters for office buildings to improve their profit. O&M have been implemented in this process model as an important factor (Shin *et al.*, 2018). O&M expenses have been studied by reviewing different factors of building maintenance. In the study, different problems and issues in building maintenance scenarios in Malaysia are discussed to find solutions to reduce the costs (Che-Ghani *et al.*, 2016).

A review of maintenance management systems was conducted (Yousefli *et al.*, 2017) to identify and classify current literature and studies in the field of maintenance management for health-care facilities. Several applied methods, such as integrated performance-based maintenance management and area-based weighting method were discussed by authors. In addition, another paper has reviewed different maintenance strategies (pro-active, preventive, predictive and corrective) and investigated their relationship with customer satisfaction in the case of health-care facilities and hospitals to review different types of maintenance strategy applied to maintain facilities while satisfying the end-user to obtain a correlation result between types of maintenance strategies and customer satisfaction (Rani *et al.*, 2015).

Recent works on the data center network (DCN), which is an important network connecting various devices in the DC infrastructure, was reviewed (Xia *et al.*, 2017). The researchers have classified main studies in this area and used surveys to describe their findings and to represent future research opportunities. In addition, a review of the FM and maintenance strategies has been recently conducted focusing on facility maintenance and management concepts of DC operations. The study provides future research work for having more reliable operations in DCs (Bieser and Menzel, 2019).

In addition to review papers regarding O&M, some recent research work discussing the relation of FM and maintenance have been found and included in this section. The impact of failures such as natural disasters or manmade disasters on the facility management organization has been studied to analyze its vulnerabilities. The study was performed by simulating and modeling the organization network using surveys, defining the failure

modes and evaluating the system's stability. The O&M of the infrastructure were considered with various elements and, eventually, the essential parameters for the organization's maintainability have been obtained (Tang *et al.*, 2017). To study the role of maintenance in facility management, research has been done in the case of building facilities by applying a fuzzy-AHP-based decision support system (FADSS). By using this method, the optimal and proper maintenance strategy considering the improvement of efficiency and minimizing maintenance cost has been achieved (Pun *et al.*, 2017).

In the areas of building information modeling (BIM), FM and maintenance, some research works have been done. BIM and augmented reality (AR) are integrated together to provide an environment that is ambient intelligent (AmI). This approach could assist facility management in performing maintenance tasks. The research considered health-care facility management as the area of application (Irizarry *et al.*, 2014). The importance of BIM and big data has also been discussed to present a model that could be used in maintenance and FM. Based on the research, maintenance information, as an important part of FM, is required to create the conditions data model (CDM). Researchers have concluded that applying the CDM framework has several advantages for building owners, service providers and users by enhancing the quality of service (Halmetoja, 2019).

The field of green maintainability in buildings has become an interesting topic for researches. Studies have been conducted on the green building considering FM and O&M. In addition, high-rise vertical greenery systems (VGS) have been studied by conducting interviews and surveys to discover their main challenges and issues regarding maintenance costs and considerations (Chew *et al.*, 2017; Conejos *et al.*, 2019).

A comprehensive search has been performed to find published research works on topics related to operations, maintenance and management of DCs. Based on findings, literature review regarding O&M management issues for DC and IT facilities is very limited. Therefore, according to the lack of such a comprehensive review, this paper is focused on identifying and organizing the available literature, mostly during the past 10 years, about current strategies and solutions proposed by researchers for managing the O&M issues for the DC infrastructure. Also, optimization algorithms were implemented and applied by researchers to adjust operational components in DCs. These methods are reviewed systematically and included in this paper.

In this review, the authors have discovered the most recorded keywords in publications related to O&M management in the Engineering Village – Elsevier database. To limit the results, the search has been narrowed down to specific terms including maintenance, decision making, reliability and scheduling. More than 50 important keywords representing the topics and methods of these publications are found and presented in Figure 1. Achieving these keywords is useful for demonstrating the main concerns and trends regarding the O&M management field. In addition, frequent keywords used in the literature by researchers about DC's O&M have been obtained separately and shown in Table I.

The next sections of this review paper are organized based on the following categories: the infrastructure management (IM) topic in DCs is introduced and discussed in Section 2. A review of recent studies and research work in the field of operations management (OM) in the DC facility is expressed in Section 3. Section 4 describes the literature and publications regarding the maintenance management of DC infrastructure by illustrating relevant methods and models. In Section 5, a discussion based on Sections 2-4 is provided to summarize the reviewed papers and determine the main research gaps and limitations, obtained from the literature. Finally, Section 7, a summary of this paper including the main

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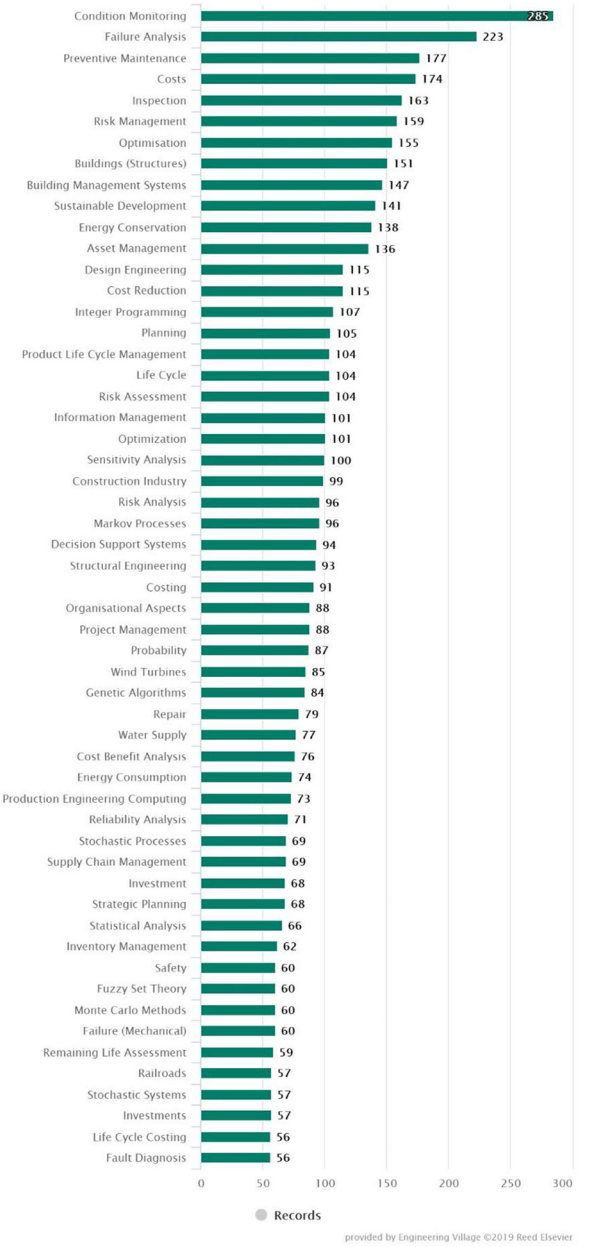

Source: Elsevier (2019)

Figure 1.
Most used keywords in publications related to operations and maintenance management

Data center design and planning	Data center operations and maintenance (O&M) management
Keywords	
Data center	Maintenance
Data center infrastructure management (DCIM)	Facility management
Cooling systems and technologies	Performance
Cloud computing (cloud) data center	Simulation
Project management	Operations and maintenance (O&M) management
Network topology	Energy
Building(s)	Cost
Modular data center (MDC)	Maintenance scheduling
Data center networking (DCN)	Quality
Internet data centers (IDC)	Reliability-centered maintenance (RCM)
Event management	System availability
Sustainable construction management	Power management
HVAC system	Key performance indicator (KPI)
Internet of Things (IoT)	Information technology infrastructure library (ITIL)
	Failure
	Efficiency
	Maintenance effect
	Preventive maintenance
	Reliability-based maintenance
	Task scheduling

Table I. Most frequent keywords in the topic of data center design, planning, operations and maintenance management

research gaps and limitations is presented, and according to the findings from the previous section, appropriate ideas for future research directions are demonstrated. To represent the topics covered and reviewed in this paper more clearly, the paper's structural diagram is provided in Figure 2.

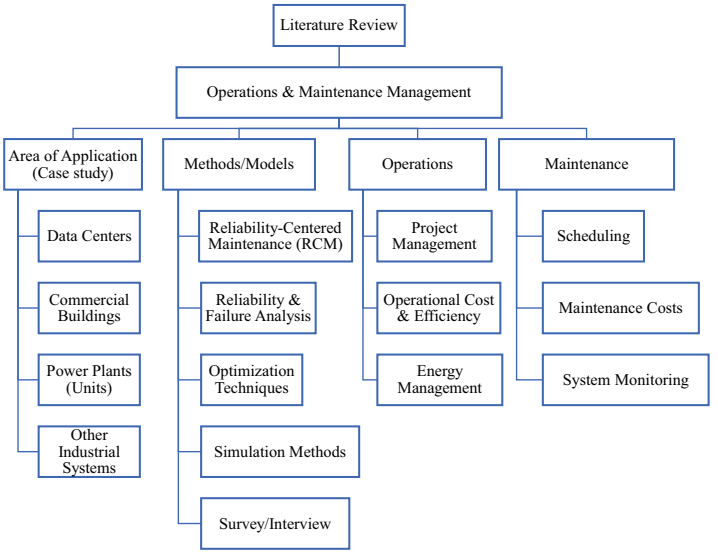

Figure 2 Structure of this literature review paper

3. Data center infrastructure management

It is worthwhile to note that the DC infrastructure expense makes up to one-third of the total IT budget. This amount of investment is also used for DC operations. Unfortunately, companies have not completely focused on applying new methods, models and technologies to manage their capital expenses related to the DC infrastructure operations. This section focuses on the DC infrastructure management (DCIM) definition which has been introduced recently to assist in managing and monitoring several systems in a DC (Geng, 2015). Other studies have considered the DCIM defining it as a combination of the IT systems management with FM systems (Hubbell *et al.*, 2015). Before introducing DCIM, IT professionals were engaged only with IT equipment (servers, storage, networks, etc.) and facility managers took care of the DC building. But now because of increasing investments in high-performance computing (HPC) and cloud services infrastructure, it would be more effective if DC and its IT equipment be considered as one single system to bring more benefits. Some useful tools and methods, such as the Big Data model, 3D gaming technology and 3D monitoring and management (MM3D), which have been developed at MIT Lincoln Laboratory, were used to provide in-depth analysis of historical trends and conditions to optimize operations for reaching higher efficiency and reliability. Managing to compute resources and identifying troubles in the system and providing real-time insight into critical facilities systems, IT infrastructure, lifecycle management, cost reduction strategies and historical analytic capabilities with less effort and cost are other objectives of these methods. The US Government along with major companies (Google, Microsoft and Facebook) are studying the expenses for the DCIM implantation. Based on the results, some future works could be conducted toward developing a smart tool for green DCs (such as delaying the jobs until the evening hours or off-peak hours because of lower electric rates) (Hubbell *et al.*, 2015). Researchers have noted that DCIM is used to monitor, check, control and manage the energy usage of IT devices in a DC. It has principle points which are input, process and output. Devices such as sensors are considered as input components and are transmitted in the process stage to collect and analyze various data and finally are offered to the users as the output component. The information of DCIM assists DC asset management as a useful source. Important parameters such as space, power and cooling capacity could be predicted well. The availability of DC is improved by receiving information from the current power level and cooling capacity. Operational costs will be decreased by improving total efficiency (Abbas *et al.*, 2015).

4. Data center operations management

An operation is defined as a task that should be conducted in a service many times during an application's performance (Diouri *et al.*, 2015). Because DC should always provide the required services and operations, any interruption in its services will cause major problems and will have negative effects on the whole system. Therefore, fast recovery of operations is an essential issue in the case of DCs. Providing cloud services has become an important factor for DCs because of giving information to numerous users worldwide which are using several types of intelligent and portable gadgets and devices. Reports prepared by organizations indicate that the total DC traffic will reach up to 8.6 zettabytes in 2018 (Janacek and Nebel, 2017). In Section 3 of this paper, the authors have presented recent research and studies on various aspects of DC operations such as DC cooling technologies, quality and project management in a DC, issues in DC networks operations and the operational expenses.

Selecting the appropriate cooling system will also reduce the O&M costs and increase the overall performance of a DC. The investigation is in progress on newer technologies such as

free-air cooling and liquid cooling to be used instead of the traditional air cooling system (Li *et al.*, 2016). Researchers are evaluating economic cooling systems for DCs to have them energy-optimized. By performing numerical and simulation studies and considering a dedicated cooling system and design conditions, selecting the best system could be possible (Cho *et al.*, 2015). Because cooling devices consume the most energy in DCs, energy-saving methods are being tested in case studies to obtain significant energy saving (Hassan *et al.*, 2015).

4.1 Quality control and project management in data centers

Quality management system and quality control procedures are important factors in managing efficient DCs. A recent study has identified service quality assessment as a required tool to be applied during the operation of a DC. Several analyses were performed on optimizing the cost of service quality by considering some factors such as job numbers to decrease waiting times and loss rate which have a significate effect on improving quality and finally minimizing its cost (Bayati, 2016). In addition, a quality service model was implemented by scholars to improve the system reliability in a DC. To reach customer expectations, service quality is a key issue that should be have been taken into consideration seriously. The analytic hierarchy process (AHP) method is used to develop a quality service model. Several values of service quality (such as reliability, credibility, security, access and competence) were selected and organized to make the best decision for the costumer's satisfaction. Their proposed model integrates the system from the design and planning stage to the controlling and operations level. Based on the methodology in their study, conversations have been performed with DC companies, IT specialists, operation managers and other technicians in this area to find the main design standards, DC design shortcomings and its framework. As mentioned, the AHP method is used to obtain the service success for problems that occurs in a DC complex. However, there are some limitations, such as addressing only controllable and productive factors (internal factors), in their study (Wiboonrat and Kaewsiri, 2014). About DCPM, newer research has implemented the integrated ISO 26702 and IEEE 1490 standards in the Data Center Project (DCP) while investigating the stakeholder's participation. The target was developing a framework for DC systems engineering (SE) via process integration regarding both ISO and IEEE standards. The highlighted objectives of the study were minimizing user's complaints on requirements that do not match with DC specifications and design, finding the effect of these modifications on the system breakdown structure (SBS), comparing the effectiveness and trade-off analysis in the system and, finally, obtaining the role of standards in DC project success. The researcher has applied international project management standards with project management tools and techniques for DC. Also, modeling, prototyping and development strategies were used (Wiboonrat, 2016). The project success model has been defined and elaborated in the literature, which considers the time domain of several activities. These tasks include operation management, marketing management and service management. Leading a project to success is an uncertain strategy and dynamic solutions. It has both short project success corresponding to reliable operations and long project success which is related to time. Thus, OM and marketing management are the most important parameters of project success. In a DC, the most critical factors based on recent studies are the design and planning stage and, then, implementing, monitoring and controlling the system. Moreover, the system maintenance and operations process is taken into consideration. The devices and components such as networks, servers, storage, operating systems and applications are important. Also, the installation and operation of applications

need to be considered to find critical factors that have an effect on project success or service quality (Wiboonrat and Kaewsiri, 2014).

4.2 Data center network operations

The DC network or DC networking (DCN) has been considered by researchers (Xia *et al.*, 2017). It is an interconnection in the DC infrastructure which is designed specifically. To optimize DC operations, the DCN has an important effect. In a DC, a trade-off among operation costs and the availability of required services should be considered. This research reviews some critical issues of DCN operations such as the huge scale of DC because of having numerous servers. This causes economic, design, operations and other considerations. For instance, there are more than 100 Microsoft DCs worldwide, each having a tremendous number of servers. Another challenge is a high quantity of online services available in a DC which creates high traffic and workload. High power and energy usage, as mentioned before in the Section 1, is one of the main concerns in many studies and it is specially investigated in this survey. Finally, avoiding or reducing failures during a DC operation is evaluated. While DC should be available all the time, having a strong system is an essential matter. Thus, monitoring various component failures and providing recovery strategies is a must in the DCN (Xia *et al.*, 2017). An important cause of failure in a DC, discussed by researchers, is the heat waste produced by the high-density blade servers located in the DCs. This heat wastage increases the failure of hardware, and thus, the DC maintenance costs will rise significantly (Wang *et al.*, 2009). Internet Data Centers (IDCs) have been studied in terms of operational issues (Wang *et al.*, 2012). As they are an important type of cyber-physical systems (CPCs), they should provide dependable operations for many online services (e-mail, blogging, social networks, online business, etc.). While these services are increasing every day, their operational costs (running the system, cooling equipment, etc.) are also rising because IDCs use a considerable portion of the electricity market. Study on how to minimize the power usage expenses was performed by presenting a supply function by researchers. Their objective was to optimize electricity costs related to IDC with the help of nonlinear programming. The corrected marginal cost (CMC) algorithm has been introduced and used to solve the optimization problem in an efficient manner. Based on studies, the operational costs could be reduced up to 45 per cent by taking advantage of various energy price in different locations (Wang *et al.*, 2012).

4.3 Data center operational costs

Efforts have been taken to reduce the operational risk, improve the responsiveness and facilitate behavior predictions in the DC infrastructure by using low-cost and low-power wireless sensors to monitor variables such as power, temperature, humidity, airflow, differential air pressure, water, closures, motion and vibration in the DC facility (Levy and Hallstrom, 2017). The objective of their study was to gather important information to assist users to make more informed decisions, reduce the downtime and cost of operations, improve energy efficiency, perform energy audits, plan space usage and develop predictive behavior models. Finally, a real-time monitoring and management approach for the DC infrastructure was proposed. As some future research opportunities in this field, predictive modeling can be considered to simulate and forecast the DC's performance and behavior in the future. Moreover, the simulation tool is useful for validating the model and analyzing different scenarios (Levy and Hallstrom, 2017). Other methods or models have been also used to address reducing the costs of operations in DC. An approach is proposed (Saha *et al.*, 2016) to optimize the use of resources in DC. According to their study, the operational expenses in a DC, depending on the type of operations, could be generally between 10 and

25mn dollars per year (Saha *et al.*, 2016). The hardware and software in a DC, both spend about 40 per cent of DC's operational costs. Therefore, a revenue optimization model is developed and implemented for maximizing the revenue in a DC while minimizing the investment cost. To achieve this objective, the Cobb–Douglas production function is used and calculated by the researchers while considering budget constraints. Maximizing the production, minimizing the cost and maximizing the profit for a typical DC enterprise were modeled. The inputs were cost of servers, infrastructure investment, power costs and networking costs. Finally, the solutions for having the maximum revenue in a cloud DC are obtained (Saha *et al.*, 2016). Different energy scenarios and power management strategies are analyzed based on the number of servers in the DC (Janacek and Nebel, 2017; Postema and Haverkort, 2018). To evaluate and test the quality of power management strategies in DCs, important parameters including stability, efficiency, adaptability and robustness have been measured for each power management strategy. Regarding the desire quality metric, the optimized strategy may be different. Thus, the selected power strategy depends on which quality parameter is the most important one for a typical DC (Postema and Haverkort, 2018).

4.4 Information technology infrastructure library method

To explore and improve the DC operations in a cloud computing environment, the information technology infrastructure library (ITIL) method was introduced by scholars (Bai and Geng, 2015). ITIL is defined as a set of IT service management standard libraries and based on a process. It is applied to manage the IT infrastructure process. Having efficient, safe and stable operations in DCs, forming an operation management practice under the cloud computing environment were the objectives of their research work. In addition to the ITIL, the advantages of automation and maintenance tools in DC operations have been elaborated. These tools are helpful in making a unified management system consisting of physical and virtual resources. By applying automation tools, the O&M management could become effective, appropriate, smart, united and integrated to be used in a cloud DC (Bai and Geng, 2015).

4.5 Data center reliability and failure analysis

Regarding the reliability analysis, a study on modular data centers (MDCs), as a relatively new type of DCs, is performed recently. MDCs are defined as the DCs which have improved design and high resiliency, especially in remote regions. They could extend the ICT to places that have limitations in terms of maintenance support. MDCs are made up of independent and self-directed modules. They are constructed in standard scales so that they could be transported more easily in containers (Farrahi Moghaddam *et al.*, 2017). Different components of an MDC, such as serves, switch and links, are considered in terms of their failure during operation. For this analysis, the Monte–Carlo approach has been used to investigate each components' performance during its lifespan. The scholars have selected three main network topologies of the MDC and evaluated their performance and resiliency (Farrahi Moghaddam *et al.*, 2017).

Continuity of the service is a key aspect of any system. Particularly, in a DC, proper facility management is an essential issue for improving energy efficiency and reducing operational costs. A benchmark reliability analysis identifying failure modes of key components in a DC is needed, which can estimate the distribution of them over their service life. To design DC facilities with excellent reliability, minimizing DC's downtime will save organizations large amounts of money in the future. It should also be noted that DC carries the information system related to the host network and stores them in devices. Thus, for

having the best DC performance, managing and maintaining its system a key parameter online services use the data stored in DCs, which should be accessible and available instantly. The quantity of stored data in DCs is increasing (as mentioned in the introduction) because of using Infrastructure as a Service (IaaS) applications (computers and virtual machines used by remote users which are using services such as Amazon Web Services) and social media (Janacek and Nebel, 2017). Recently, practices have been taken place in DCs to assure successful data recovery. Moreover, critical applications should be able to restore for enabling the continuity of operations when a disruption occurs in DC services (Gómez *et al.*, 2019; Bai and Geng, 2015).

5. Data center maintenance management

In the area of maintenance management, several studies have been performed and various methods and models have been used, implemented and developed by scholars. In this section, efforts have been taken to cover most of the recent studies related to this topic by investigating the maintenance management issues of DCs and IT infrastructures. The methods and models applied in various industry sectors will be also discussed. This approach could assist in finding new methods to develop an optimized maintenance management schedule and framework for DCs.

The maintenance stage in every system is very important and requires major attention. Especially in the case of DCs, with having several critical components running all time, a proper maintenance management system proving various maintenance jobs is needed to monitor DC operations, find component failures and provide repairing strategies (Xia *et al.*, 2017). The importance of DC maintenance has been highlighted by some scholars. Studies on various solutions have been performed by them to reduce energy consumption and improve the reliability, quality and performance of most important systems, subsystems and components in DCs. Design methods and techniques are implemented to overcome main issues by improving cooling systems and technologies and managing the servers and other key components while minimizing O&M costs. Because of the conducted research and estimations, nearly 80 per cent of total costs in a DC are related to the maintenance expenses (Saha *et al.*, 2016).

A brief study on the economic evaluation of effective computer-aided facility management (CAFM) software implementation in manufacturing companies was performed. The focus of the study was on the manufacturing part of a mechanical company in the Czech Republic. The goal was analyzing machinery maintenance as a critical element of FM in the industry (Poór *et al.*, 2014). The human performance during maintenance operations is an important issue which has its own impacts. This factor has been presented and focused on by researchers. They have presented a data collection and analysis procedures for maintenance operations in ships and marine systems. Information was gathered from engine departments (ED) and deck departments (DD) through a structured questionnaire. However, the study is limited to process marine systems, and no specific maintenance plan, schedule or system is proposed and developed (Islam *et al.*, 2018)

The reliability-centered maintenance (RCM) optimization method, as a popular maintenance management model, has been used by researchers, especially for power distribution units (Yssaad *et al.*, 2014; Piasson *et al.*, 2016). RCM is used to perform preventive maintenance in a system. Introducing and implementing an economic maintenance program for electric power distribution systems is performed by studying an electrical distribution station located in Algeria, as a case study. The objective of the research was to reduce the maintenance cost by focusing on the system's most important functions and ensuring safety by performing preventive maintenance actions and maintain

the functionality at a low cost (Yssaad *et al.*, 2014). In another case study, an electric power distribution system (EPDS) located in Brazil was selected and a complex mathematic model was developed and used, focusing on scheduled maintenance actions and the unreliability index caused by the maintenance programs. The model minimized preventive maintenance costs while improving the reliability index for more than 700 components and 3 feeders operating in this EPDS (Piasson *et al.*, 2016). Another study has also implemented the RCM strategy in 2016 by using the maintenance history data of a process plant manufacturing titanium dioxide. Reaching high availability of production equipment and reducing maintenance costs were the main objectives (Vishnu and Regikumar, 2016).

The availability-based maintenance (ABM) strategy has been recently applied in a domestic hot water subsystem (DHW) in the building's HVAC system. The reason for using this framework was to reduce maintenance costs while improving the system's reliability. Also, with the assistance of the keeping system available (KSA) method, optimization of maintenance scheduling has been performed regarding the system's reliability. However, the impact of other types of subsystems (such as parallel and standby) on the maintenance scheduling and the system's availability was not discovered. Moreover, the maintenance cost was not minimized in their study (Pourhosseini and Nasiri, 2018). It should be noted that the KSA method has been previously presented and applied to optimize the maintenance programs for critical elements in thermal power stations. The researchers found that by using this method, a more appropriate maintenance schedule could be obtained, and thus, the failures are reduced and the maintenance expenses are decreased (Zhang *et al.*, 2002). Moreover, scholars have studied further for improving the method based on reliability for increasing total system availability (Zhang and Nakamura, 2005).

6. Research gap analysis, limitations and future research

Based on the reviewed publications and research works, which were discussed in the previous sections, it is observed that a considerable number of works have been done in the fields of system operations, maintenance, reliability and availability along with proposing new frameworks, methods and models to improve the performance of several systems in the industry. This paper's objective was to find and discover studies which have focused on DCs. Only a few research works were found in this area of application. In this section, all publications have been organized in Table II based on their topic of research, methodology and their area of application.

In the next step, based on the literature discussed in the previous sections, significant challenges and issues which have been addressed by researchers are presented. However, some important topics about O&M management in DCs have not yet studied by scholars. These topics are summarized and discussed as future research developments in this section. Hence, remaining research works in this field and the most important research gaps and limitations are obtained.

According to the literature, authors have presented valuable methods and models for DC operations monitoring and proposed a monitoring system to improve the reliability and reduce the downtime and cost of operations (Hubbell *et al.*, 2015; Levy and Hallstrom, 2017). In addition, in the design and planning stage of DCs, important studies have been conducted about the DCP and developing a framework for DC SE to improve customer satisfaction (Wiboonrat and Kaewsiri, 2014; Wiboonrat, 2016). Their studies could be extended by adding a complete integrated reliability and availability analysis for DC and calculation of availability and maintenance cost for each component in the DC infrastructure.

In terms of DC O&M, scholars have conducted research on operational issues of internet data centers (IDCs) and proposed a supply function to model the market power of IDC and

Table II. Taxonomy of recent publications based on their topic, methodology and case study

Author(s)/ Developer(s)	Topics of research: Operations and maintenance management								Methodology			
	Project and quality management	Operational cost	Operations efficiency	Cooling systems and equipment	Energy and power usage minimization	System performance	Maintenance management, planning and scheduling	System monitoring and management	Maintenance cost	Reliability and failure analysis	Reliability-centered maintenance (RCM)	Keeping system available (KSA)	Analytic hierarchy process (AHP)
Zhang, Nakamura and Hatazaki (2002)							✓			✓		✓	
Zhang and Nakamura (2005)							✓			✓			
Wang *et al.* (2009)		✓					✓		✓				
Guenter *et al.* (2011)					✓					✓			
Wang *et al.* (2012)		✓			✓								
Irizarry *et al.* (2014)							✓	✓	✓				
Poór *et al.* (2014)					✓		✓	✓		✓	✓		
Wiboonrat and Kaewsiri (2014)	✓	✓	✓			✓							✓
Yssaad, Khiat and Chaker (2014)							✓			✓	✓		
Zhan and Zhang (2014)			✓					✓					
Bai and Geng (2015)			✓					✓					
Cho *et al.* (2015)			✓	✓	✓								
Hassan *et al.* (2015)		✓	✓	✓	✓								
Hubbell *et al.* (2015)		✓			✓			✓					
Khan and Zomaya (2015)							✓	✓					
Rani *et al.* (2015)							✓	✓	✓				
Bayati (2016)					✓	✓							
Cho and Kim (2016)		✓		✓	✓								
Kadir *et al.* (2016)			✓				✓	✓					
Li *et al.* (2016)		✓		✓	✓								
Piasson *et al.* (2016)							✓			✓	✓		
Saha *et al.* (2016)		✓	✓		✓				✓				
Scheffer *et al.* (2016)							✓						
Vishnu and Regikumar (2016)							✓		✓	✓	✓		✓

(*continued*)

Table II.

Author(s)/ Developer(s)	Topics of research: Operations and maintenance management									Methodology			
	Project and quality management	Operational cost	Operations efficiency	Cooling systems and equipment	Energy and power usage minimization	System performance	Maintenance management, planning and scheduling	System monitoring and management	Maintenance cost	Reliability and failure analysis	Reliability-centered maintenance (RCM)	Keeping system available (KSA)	Analytic hierarchy process (AHP)
									✓				
Wiboonrat (2016)	✓					✓							
Farrahi Moghaddam *et al.* (2017)										✓			
Levy and Hallstrom (2017)		✓			✓			✓					
Pun *et al.* (2017)			✓				✓		✓	✓			✓
Tang *et al.* (2017)							✓						
Beauregard and Ayer (2018)		✓	✓				✓		✓				
Islam *et al.* (2018)							✓						
McArthur and Bortoluzzi (2018)							✓		✓				
Postema and Haverkort (2018)					✓								
Pourhosseini and Nasiri (2018)							✓			✓	✓	✓	✓
Shin et al.(2018)							✓		✓				
Braglia *et al.* (2019)							✓			✓	✓		
Conejos *et al.*, 2019)							✓		✓				
Erozan (2019)							✓			✓			
Gómez *et al.* (2019)							✓						✓
Halmetoja (2019)							✓						
Hameed *et al.* (2019)							✓						
Kian *et al.* (2019)							✓						
Mollahassani-Pour *et al.* (2019)							✓						
Sayyah *et al.* (2019)		✓					✓			✓			
Sheng and Prescott (2019)							✓						
Wang *et al.* (2019)							✓						
Zhong *et al.* (2019)							✓		✓				

(*continued*)

Table II.

Author(s)/ Developer(s)	Methodology						Area of application				
	Survey – interview	Service quality assessment	Monte–Carlo approach	System optimization	Simulation methods	Information technology infrastructure library (ITIL)	Big data/ data collection	Data centers	Power plants (units)/ related components	Other industrial systems	Commercial buildings	No specific case study
Zhang, Nakamura and Hatazaki (2002)									✓			
Zhang and Nakamura (2005)				✓					✓			
Wang *et al.* (2009)				✓	✓			✓				
Guenter *et al.* (2011)				✓				✓				
Wang *et al.* (2012)				✓				✓				
Irizarry *et al.* (2014)					✓						✓	
Poór *et al.* (2014)				✓						✓		
Wiboonrat and Kaewsiri (2014)		✓						✓				
Yssaad, Khiat and Chaker (2014)									✓			
Zhan and Zhang (2014)						✓		✓				
Bai and Geng (2015)						✓		✓				
Cho *et al.* (2015)					✓			✓				
Hassan *et al.* (2015)				✓				✓				
Hubbell *et al.* (2015)							✓	✓				
Khan and Zomaya (2015)					✓			✓				
Rani *et al.* (2015)	✓										✓	
Bayati (2016)		✓		✓				✓				
Cho and Kim (2016)				✓							✓	
Kadir *et al.* (2016)								✓				
Li *et al.* (2016)				✓				✓				
Piasson *et al.* (2016)									✓			
Saha *et al.* (2016)				✓				✓				
Scheffer *et al.* (2016)					✓					✓		
Vishnu and Regikumar (2016)										✓		
Wiboonrat (2016)		✓						✓				

Table II.

Author(s)/ Developer(s)	Survey – interview	Methodology: Service quality assessment	Monte–Carlo approach	System optimization	Simulation methods	Information technology infrastructure library (ITIL)	Big data/ data collection	Area of application: Data centers	Power plants (units)/ related components	Other industrial systems	Commercial buildings	No specific case study
Farrahi Moghaddam *et al.* (2017)			✓					✓				
Levy and Hallstrom (2017)				✓				✓				
Pun *et al.* (2017)				✓					✓			
Tang *et al.* (2017)	✓			✓						✓	✓	
Beauregard and Ayer (2018)	✓						✓				✓	
Islam *et al.* (2018)	✓									✓		
McArthur and Bortoluzzi (2018)	✓										✓	
Postema and Haverkort (2018)				✓	✓			✓				
Pourhosseini and Nasiri (2018)											✓	
Shin et al.(2018)	✓				✓						✓	
Braglia *et al.* (2019)										✓		
Conejos *et al.*, 2019)	✓										✓	
Erozan (2019)										✓		
Gómez *et al.* (2019)										✓		
Halmetoja (2019)	✓						✓				✓	
Hameed *et al.* (2019)				✓	✓					✓		
Kian *et al.* (2019)				✓						✓		
Mollahassani-Pour *et al.* (2019)				✓					✓			
Sayyah *et al.* (2019)				✓						✓		
Sheng and Prescott (2019)					✓					✓		
Wang *et al.* (2019)				✓						✓		
Zhong *et al.* (2019)				✓						✓		

minimize the electricity cost (Wang *et al.*, 2012). They also applied the ITIL V3 as an operations management strategy to explore and improve the DC operations in a cloud computing environment. O&M services for cloud computing DC are also used to provide an overall, comprehensive, standard and automated monitoring (Zhan and Zhang, 2014; Bai and Geng, 2015). Further topics such as failure analysis, proposing an optimized maintenance plan and model and validating the results in real DC case studies are highly recommended.

In the area of system reliability, a study has taken valuable effort to analyze the resiliency for MDCs by identifying the critical components and calculating their failures. The performance of the component's design has been evaluated (Farrahi Moghaddam *et al.*, 2017). This research procedure can be applied in general and traditional DCs by adding system availability analysis and obtaining an efficient maintenance schedule.

In other industrial systems and case studies such as power plants (Yssaad *et al.*, 2014; Yssaad and Abene, 2015; Vishnu and Regikumar, 2016) and HVAC systems (Pourhosseini and Nasiri, 2018), several studies have been done to achieve system's availability, obtain a maintenance schedule, reduce maintenance costs and improve the reliability. These methods and models could be also applied to DCs in future research to obtain an appropriate maintenance-scheduling model.

According to the gaps mentioned above, future research directions could be classified into two main categories from theoretical and practical perspectives.

6.1 Theoretical perspectives

From the theoretical point of view, it should be noted that there are different levels of availability requirements for DCs provided by the Telecommunications Industry Association (TIA) and Uptime Institute standards (ADC Telecommunications Inc., 2006; Gabriel, 2014; Uptime Institute, 2014). Based on these requirements, the DC infrastructure is categorized into four different tiers and levels. Tier 1 DC has a basic level of availability (99.671 per cent), whereas Tier 4 DC has the maximum availability level (99.995 per cent). These levels of availability and downtime express the importance of DC infrastructures and the need for an ABM scheduling model. Most of the current maintenance management and scheduling models have considered cost minimization whereas the risk parameter has not been fully implemented. In the case of DCs, a maintenance management optimization model has to be implemented integrating cost and availability factors regarding DC's availability requirements. We are also in need of models to incorporate organizational (such as change management capabilities) and external risks (such as extreme weather conditions) into failure prediction and reliability analysis of DC infrastructures, which has been widely studied in IT domain (Mafakheri *et al.*, 2012) but is missing in case of DCs facility management research.

6.2 Practical perspectives

In future research, the maintenance management models for DCs need specific management practices and benchmarks, which are not much available in the current literature. Because of the nature of assets available in DCs, there are several types and categories of assets in a DC which should run 24/7. Thus, to perform best maintenance management practices for DCs, companies and their facility managers need to share their experiences in this matter. Specific benchmarks, codes and handbooks are recommended to be developed and customized for DCs, to obtain and implement a specialized availability-based optimized maintenance-scheduling model for the DC industry. Also, the condition-monitoring process is highly

important when dealing with various types of mechanical, electrical and networking, assets in DCs.

Although this paper has reported several methods, techniques, models and frameworks regarding O&M management systems in different cases, specifically in DCs, there are still remaining gaps and limitations in this area that should be concerned. In both the academic and industrial sectors, the attention to the DC infrastructure and facility is increasing in terms of obtaining reliable and effective solutions for optimizing DC's operations. In addition, these solutions should assist maintenance managers to reduce maintenance costs. So far, studies have been conducted mostly on the maintenance monitoring for DCs and new technologies in this area. Also, several publications have investigated the solution for minimizing power and energy consumption of DCs. Although each of these research works has reported valuable information and solutions, new studies are required to be performed for addressing an optimized maintenance schedule and management system. Similar works are done in other industrial systems but in the case of DCs, research works have remained limited and some important issues are not considered.

Regarding the issues discussed, a comprehensive framework is required to analyze the failure rates and modes for the components in a DC and then calculate the availability of the components while considering the cost of maintenance tasks for each component. With this approach, the subsystems and components could be organized based on their maintenance schedule, the parts which need preventive maintenance are defined and the issue of system's over maintenance is avoided.

7. Conclusions

In this paper, efforts have been made to represent a critical literature review on the topic of operations and management. The objective was to discover new publications in this area, and especially for DCs. In the previous section, a summary of the literature is reported to clarify the research topics, methodologies and case studies to obtain the remaining unstudied works, which are the research shortcomings. As represented, the literature in the field of DC maintenance is not rich, and thus, more studies have to be performed in the future.

An extensive reliability, failure and availability analysis, integrated with maintenance scheduling, must be implemented for DCs. Moreover, the maintenance plan could be optimized by applying various optimization techniques to decrease the costs of maintenance tasks while addressing the system's availability requirements. The DC facility and infrastructure with all systems, sub-systems and components should be carefully considered in future research works.

Identified gaps and limitations in the reviewed studies express the essential need for more efforts in conducting research in the field of maintenance planning, scheduling and management for DCs to reduce the maintenance costs while improving the performance and reliability of the DC system. As DCs have been dealing with several practical issues such as high maintenance costs, this paper provides a structured way of classifying the literature with respect to these issues. In addition, several of the reviewed papers were based on real case studies. Therefore, the outcomes of this paper could have many benefits for practitioners.

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