# Emerging Trends in Data Center Management Automation

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***Abstract*– New and emerging technologies have consolidated the Fourth Industrial Revolution, an era of cyber-physical systems, where the physical and digital worlds are closely connected. While most of the world is being impacted by a pandemic, data centers have managed to keep people connected and keep the economy afloat. As such, they are witnessing an unprecedented need for automation of their monitoring and management processes in order to minimize reliance on human interaction. A growing number of new technologies are transforming mission critical facilities into a highly connected, smart, and more efficient, productive and sustainable industry. Vast amounts of data are being collected in real-time, and processed to predict behavior, to produce actionable recommendations, and to improve decision-making. This paper summarizes the three main emerging technological trends, identified by the authors, which enable these processes in data center management automation: 1) intelligent monitoring and management systems using data science; 2) simulation tools incorporating artificial intelligence and digital twinning; and 3) robotics for process automation.***

***Index Terms* – Data center, monitoring, management, data science, simulation, robotics.**

## I. Introduction

Data centers comprise information technology (IT) equipment and its supporting infrastructure such as power, cooling, telecommunications, fire systems, security, and automation. These mission critical facilities process and store information securely, and provide reliable access to it. They are dynamic, meaning new equipment can be added, existing equipment can be upgraded, obsolete equipment may be removed, and legacy and new equipment may be in use simultaneously. Data centers are energy intensive facilities, and are accountable for approximately 1% of the electricity consumption worldwide [1].

The world is facing a pandemic, and data centers have, to an extent, mitigated its impact. Data centers have allowed us to continue many tasks of our daily lives in a virtual format, thus contributing to the economy which nowadays relies heavily on technology. The Cybersecurity and Infrastructure Security Agency (CISA) has issued guidance on the essential critical infrastructure workforce in COVID-19 Response' [2]. Data centers are identified as essential and mission critical businesses during the COVID-19 crisis.

Our increasing reliance on data centers, and its expected growth, has created an urgent need to intelligently monitor and manage them, improving their effectiveness, productivity and sustainability, while reducing their overall risk of failure. The consequences of downtime for a data center in general imply the lack of access to information and services which entails costs and intangible losses.



We are witnessing an acceleration of technological innovation, and emerging technologies have significantly contributed to the management automation of mission critical facilities. Identifying emerging trends guides us to visualize the possible new normal in the near future, since previous strategies may not always work. Thanks to the advances in intelligent monitoring, robotics, simulation and artificial intelligence, we can now recognize patterns, behaviors and predictions almost instantly. Based on their previous knowledge, the authors have identified the three main technological trends impacting data center management automation that reduce human interaction. They are: 1) intelligent monitoring and management systems using data science; 2) simulation tools incorporating artificial intelligence and digital twinning; and 3) robotics for process automation. These advancements will have a significant and disruptive impact on millions of data centers worldwide.

The motivation of this paper is to present an overview of these technological trends, their impact on the industry and some of the challenges they face. This paper also opens doors for future research on the best way to implement these emerging trends in existing or new data centers. The remainder of the paper is organized as follows: section II outlines legislation, standards and best practices related to data centers, section III describes intelligent monitoring systems, section IV describes simulation tools, section V describes robotics, and section VI concludes the work and suggests future research.

## II. Legislation, Standards and Best Practices

Organizations and individuals around the world have contributed to create standards and best practices for the data center industry. Standards and best practices are a respected source of guidance when designing, building and managing data centers, from local and country codes, to performance guidelines. Although automation is a relatively new concept in the data center context, due to its relevance and high implementation rate, recent versions of most standards and best practices incorporate automated real-time monitoring processes. It is worth mentioning that legislation, standards and best practices evolve frequently to adapt to new technologies and challenges, hence the importance to identify emerging trends impacting these facilities.

Some of the main publications used by professionals include the *ANSI/TIA 942-B: Telecommunications Infrastructure Standard for Data Centers* [3], the *ANSI/BICSI-002: Data Center Design and Implementation Best Practices* [4], *the ISO/IEC 22237*: *Information technology - Data Centre Facilities and Infrastructures* [5] [6] [7] [8] [9] [10] [11], the *Data Center Site Infrastructure Standard* [12], the *ANSI/ASHRAE 90.4*: *Energy Standard for Data Centers* [13], the *ASHRAE Technical Committee 9.9* guidelines [14] [15] [16], the *BICSI-009*: *Data Center Operations and Maintenance Best Practices* [17], the *Data Center Site Infrastructure Tier Standard: Operational Sustainability* [18], the *Data Centre Operations Standard* (DCOS) [19], *and* the *Singapore Standard SS 564* (Green Data Centers) [20]. In addition, different U.S. government entities have expressed concern about data centers, and have addressed them with legislation. Recent examples include the *Energy Efficient Government Technology Act of 2019* [21], the 2019 update to the *Data Center Optimization Initiative* [22], and the *2016 U.S. Data Center Energy Usage Report* [23]. In an effort to be aligned with regulations, standards and best practices, automation is being used to improve data center management, making them more energy efficient and sustainable.

## III. Intelligent monitoring systems

The first emerging trend we present is the need for intelligent monitoring and management systems using data science. Data collection for mission critical facilities is enabled through the use internet of things (IoT) and sensing devices, where information (e.g., location, resource utilization, power, temperature, and humidity among others) can be collected in real-time and shared.

Obtaining real-time data is the first challenge, especially in existing data centers that lack adequate instrumentation [24]. There are a few solutions available when it comes to data center management platforms or software tools. One type of tool may be more suited than another, depending on the priorities and requirements, such as the following: a) DCIM (data center infrastructure management) solutions to monitor and control data center infrastructure; b) BMS (building management systems) solutions to monitor and control an entire building; c) EMS (energy monitoring systems) solutions to monitor and control mainly energy consumption; and d) CFD (computational fluid dynamics) modeling software to simulate airflow for different equipment configurations.

A novel approach for real-time monitoring of key parameters of data center infrastructure and IT equipment is described in [25] and [26]. The system is envisioned to be reliable, non-invasive, wireless, sensor-based, low-cost, and low-power. It provides real-time measurements that enable the creation of a data map for each parameter. It measures different parameters across equipment and the physical space of the facility. This approach highlights two classes of sensing devices for data gathering: power sensing devices and environmental / motion sensing devices. Furthermore, it considers platform level telemetry to access data directly from IT equipment processor.

Measurements comprise IT equipment and its supporting infrastructure. Most data center components, such as generators, automatic transfer switches, uninterruptible power supplies, power distribution units, electrical panels, and cooling systems possess communication interfaces from which real-time data is retrieved and transferred remotely through a standard protocol such as the Simple Network Management Protocol (SNMP) over TCP/IP. Environmental and motion parameters include temperature, humidity, airflow, differential air pressure, water, vibration, lighting, security and fire systems. Measuring them involves deployment of sensing devices across physical space and cabinets, and measurement points at different heights. Each sensed parameter covers a specific range. Newer technologies allow a broader range of environmental parameters.

Fig. 1 shows the cyclical process of an intelligent data center monitoring and management system. Data is collected from numerous sensing devices and equipment, and transmitted to storage devices. Since data may contain errors or missing information, this approach considers data cleansing. The vast amount of data collected must be organized to ensure that it can be integrated, shared, analyzed, and maintained. A metadata management system is recommended. The next step is data processing, to estimate different parameters and key indicators to understand how data centers behave in the present but also to anticipate potential problems. In [27] and [28] multidimensional data center key indicators are proposed to monitor data centers comprehensively, comprising performance and risk. These indicators have been recently incorporated in data center best practices [4] [17]. In [29], a data center risk assessment is discussed, and explores automation as an effective way to manage risk in a data center. Then data science is utilized for predictive and prescriptive analytics. Ultimately, data science helps to control different parameters in the data center to improve efficiency, productivity, sustainability, and operations, while reducing risk.

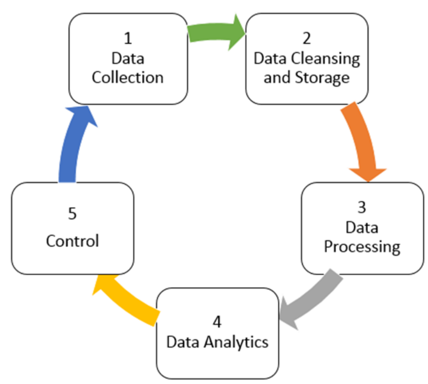


Fig. 1 Intelligent monitoring and management system

Data science, more than a technology, is a discipline that aggregates, normalizes and interprets big amounts of data using tools in math, statistics, advanced computing, data engineering, and visualization, among others. With the help of IoT, sensor-based technology, and artificial intelligence (AI), data science is being adopted in multiple processes across the data center industry to help users make appropriate use of this data, and to perform actions based on previous knowledge and real-time data. Effective data center optimization strategies include all assets to support end-to-end resource management, helping to establish an integrated strategy towards performance improvement and risk mitigation.

Some of the parameters in the intelligent data center monitoring system are based on the processing of multilayer nodes and event entities. This technique improves the knowledge about the activities in a particular node to a greater degree. One of the key benefits is that since there are vast numbers of nodes, the technique decreases the cumulative number of incidents that may be the main trigger. The goals of modern data centers are not only to ensure the maximum degree of operating reliability and availability, but also to easily detect unique incidents and improve energy effectiveness. Intelligent monitoring includes control of all the technological components and sensing devices, optimal energy support, event reporting, and reporting data to the main control element. Real-time data for central servers at the level of the main control is then the data acquired from all the distributed elements. A balance must exists between the criteria for system reliability and availability, productivity, energy consumption, and operating costs.

There are challenges to implement intelligent monitoring systems requiring continuous monitoring with automated intelligent alerts. Stability is a requirement to data center management and operations. To fulfill the growing demands of today's digital world, the resources must be permanently accessible. Although monitoring of higher-level results has been possible, it has been difficult to obtain and interpret granular data. Monitoring tools also allow an unparalleled opportunity to gather data and conduct analysis of anomalies. Better allocation of resources, proactive monitoring, predictive maintenance, and scalability are some of the challenges faced without which risk factors could be increased as the data center evolves. Power, energy, temperature and humidity are just the beginning of smart tracking of data centers. For example, fire detectors are normally connected to the fire control panel, but they can also be integrated with the monitoring tool to provide management with an incentive for early intervention and integration with other systems. All sensing devices should undergo automated testing and servicing. Emergencies are not stopped by alarms, and emergency plans should always be part of the agenda of any data center operation. Some of the big challenges faced by today's cloud and hyperscale data center architectures are scalability, latency, quality of service issues, energy efficiency, and service-level agreement assurance. In operating the data center infrastructure, the virtualization of servers, networks and computing services adds more complexities. Few other key challenges are the interconnection of IT resources to have high bandwidth connectivity and defined quality of service, high oversubscription ratio and low bandwidth, energy efficiency, and fault tolerance [30].

## IV. Simulation tools and Digital Twins

While data center monitoring solutions collect a huge amount of data and play a vital role in their own field of application, the issue arises when making these data actionable. Hence, artificial intelligence is used to develop algorithms particularly when it comes to reducing risk (e.g., thermal, energy, workloads) and optimizing the data center infrastructure. The second emerging trend is therefore the need for simulation tools incorporating artificial intelligence and digital twinning.

Simulation tools can be based on theoretical models or using artificial intelligence to learn information directly from data. In [31] and [32] a step-by-step approach to model a data center using a cyber-physical systems perspective is described considering computational and physical components. The model is validated with information from a computer manufacturer. In [33] simulations of a-priori known scenarios are developed through the theoretical model. In [34] predictions are explored without predetermined equations using supervised machine learning algorithms (e.g., nonlinear regression, support vector machine and neural network). A training data set is used to map input data to known output values and constructs a model from data collected to predict the responses for an unseen data set, to help assess different actions on the data center. Simulations and predictions are used to better understand different scenarios for IT resources, workloads and quality of service requirements.

Google has used machine learning to improve efficiency, reducing cooling consumption and overall emissions in their data centers [35]. They used a system of neural networks trained on different operating scenarios and parameters of the data centers, to create a more efficient and adaptive framework to understand dynamics and improve efficiency. Real-time and historical data (e.g., temperatures, power, pump speeds, set points) collected by thousands of sensing devices was used to train the deep neural networks model, and to predict the average power usage effectiveness (PUE), the temperature and the pressure over the next hour. Predictions contributed to simulate recommended actions. The machine learning algorithm was able to reduce by 40% the amount of energy used for cooling, with the lowest PUE indicator.

Table 1 shows an example of practical applications of machine learning in data centers. In supervised learning, inputs and outputs are provided, and used for predictions. In unsupervised learning, data is studied to identify patterns, correlations and relationships. And in reinforcement learning, a set of allowed actions and rules are given.

TABLE 1: Practical applications of machine learning algorithms

| **Learning algorithm** | **Practical application** |
|---|---|
| Supervised (labeled data) | Modeling and simulations. Behavior prediction. Resource optimization. Alarms and thresholds. Metrics and benchmarking. Image, speech and text recognition and classifications. Personalizing interaction. Fraud detection. Customer segmentation. Risk assessment. Proactive maintenance. |
| Unsupervised (unlabeled data) | Modeling and simulations. Behavior prediction. Resource optimization. Anomalies detection. Intrusion detection. Identifying like things. Assets library generation. Market analysis. |
| Reinforcement (unlabeled data) | Modeling and simulations. Behavior prediction. Resource optimization. Digital twin. Video recognition. Robotics. Navigation. Optimal resource deployment and routes. |

A digital twin is a complex, digital model of an entity or device in the physical world, linked by measured data such as power, temperature, pressure, and vibration among others. The digital twin of a data center is a simulated 3D replica of the real data center, which analyzes the current context of the data center and recommends control actions to improve specific parameters through a feedback loop.

Using modeling, validation and calibration, a digital twin of the data center is generated. It is a mixture of site survey, physical observations, data entry, and engineering analysis [36]. With the data, features, and communication skills in the digital world, digital twins represent actual objects or topics. Changes in the actual physical data center are adopted by their simulated digital twins continuously in near real-time. The technology is enabled by sensing devices gathering data in real-time, which allows to monitor the facility and simulate multiple scenarios. For more rational decision-making, the digital twin not only offers real-time knowledge but can also make predictions based on assumptions about how the different resources will change or behave. Real-time remote tracking and management, enhanced reliability, automated maintenance, risk assessment, more effective and knowledgeable method of decision support, service personalization, improved reporting and connectivity are some of the benefits of the digital twin [37].

In [38] a digital twin architecture reference model is proposed to design cloud-based cyber-physical systems. The digital twin approach can be more scalable using cloud computing infrastructure. Every physical thing is represented and connected (directly or indirectly) to a cloud based digital twin thing. If the physical world changes, a sensing device tries to update the current status to its digital twin. The system is divided into three operational modes, physical level sensors-fusion mode, cyber level digital twin services-fusion mode, and a deep integration of sensor-services fusion mode. The authors analytically modeled the computation, communication and control properties.

There are various challenges to implement this technology. Digital twin's performance relies on a bidirectional real-time connection among the physical resources and its digital twin to offer physical realism without compromise. Significant difficulties in ensuring this include spatial-temporal sensor data resolution, connectivity latency, large data volume, large data generation rate, large data diversity, high data accuracy, fast online storage and data processing. As the physical resource evolves in time, the model has to evolve accordingly while preserving backward compatibility. Because much of the physical properties on which digital twins can be imagined would need a high degree of safety and protection, greater clarity and interpretability of decisions made on digital twins will be required. It also requires models which are interpretable and physically consistent. In addition, it is important to show the digital twin to the end user in a manner that is distinct from the physical resource and simpler and more natural to function.

## V. ROBOTICS

While fixed sensing devices coupled with IoT have proven to be effective tools for monitoring data centers, facilities are demanding a more mobile technology to adequately automate monitoring and control of the facility. So, the third emerging trend is the use of robotics. A robot is in charge of automating a specific process or repetitive task. Robotics perform tasks that a worker would have to do otherwise, increasing process automation, productivity and reducing human error.

Multiple experiments have been conducted to program robots to navigate a data center and gather relevant environmental and asset data. In [39] a vision-based mobile robot with the ability to read the LEDs indicators is used to automate asset tracking, among other tasks with minimal human interaction. Encoding was done using a unique binary number. A data center monitoring system is proposed in [40] using multiple robots patrolling the physical space. They all communicate with a human administrator using wireless transmission. The system consists of robots with transponders which enables them to recognize an exact location in an indoors environment, an efficient path with minimum latency, and path adaptation, meaning the route followed by the robot must be adjusted according to server utilization, which is constantly changing in a data center. In [41], [42] and [43] an autonomous mobile robot with a laser range sensor and an internal motion unit is implemented, able to navigate the physical space, to monitor and realize measurements shared through a web based interface. The robot finds the best trajectory avoiding static and moving obstacles.

Private industry research initiatives have also been implemented for robots to monitor real-life data centers. IBM has adapted iRobot Create with additional sensing devices and their respective interfaces, a portable computer, and a webcam among other equipment to monitor environmental parameters and manage assets in a data center. This system is described in [44] and [45]. The autonomous robot navigates unknown physical spaces, uses the tiles on the data center floor and stops at unobstructed tiles to take measurements. It monitors parameters using intelligent sampling to manage energy efficiently and helps find anomalies, all at a lower cost than traditional mechanisms.

Another approach considers cloud robotics [46], which is a mix of cloud computing and robotics. It enables robots to benefit from the efficient tools of modern data centers for processing, storage, and connectivity. Moreover, it eliminates repair and upgrade overheads and reduces dependency on custom middleware. In [47] a cloud robotics platform is described for data center environmental monitoring. It is based on the Robot Operating System (ROS), which is an open source set of software libraries and tools that supports complex robotics applications. Utilizing a map that is already created in a data center for precise tracking of key measurements, the mobile physical robot can be used to autonomously navigate, identify and perform a list of measurements at various positions provided by the user through the graphical user interface. The work presents simulated results from experimentation. Fig. 2 shows the concept of a cloud robotics solution, with local and remote administrators and users.

Autonomous robots for security purposes in data centers is just another application, where deploying 24x7x365 human personnel is not feasible. In addition, robots are reliable, vigilant and adaptable. In general, they include multiple sensing devices, day/night cameras, and capabilities enhanced with artificial intelligence. Robot features include collision avoidance, facial recognition, fever detection technology, communication with humans, license plate monitoring, anomalies detection and escalation, advanced navigation including automatic door and elevator interaction. Switch is implementing artificial intelligence enhanced autonomous robots for the security of their new data centers [48].

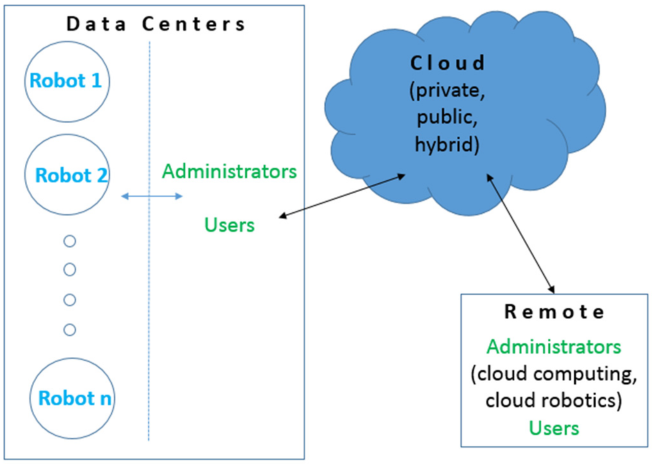


Fig. 2 Cloud robotics solution

We can also refer to software robots, digital robots, or non-physical robots. Robots such as 'chatbots' are able to dialogue with users on their computers or smartphones [49]. Open-domain dialog research explores a complementary approach using a neural conversational model to develop a 'chatbot' that can chat about virtually anything a user wants, to better deal with a wide variety of conversational topics. Such developments are expressed through a new human evaluation metric that has been proposed for open-domain chatbot, called 'sensibleness and specificity average'. This metric captures simple yet significant qualities for human communication. Tackling protection and prejudice in the models are a crucial priority field [50]. Non-physical robots are capable of extracting business insight out of large data sets for smart troubleshooting in the data center by creating better user interactions and experiences.

There are a few shortcomings from the use of robotics in the data center. First, it is an emerging field, so we are still subject to substantial trial and error before a technology is proven effective. Secondly, the cost involved in implementing robotics with reduced risk is significant. Lastly, robotics technologies require modern infrastructure and equipment for devices to be paired with, and such solutions are not viable for many existing data centers.

## VI. Conclusions and Future Research

The landscape of global data centers is changing. They require fewer employees, are more automated, and less labor intensive than older facilities. To stay competitive, legacy data centers are being upgraded with new technologies. This paper explored the three main emerging trends for data center management automation: 1) intelligent monitoring and management systems using data science; 2) simulation tools incorporating artificial intelligence and digital twinning; and 3) robotics for process automation. All three are innovative technologies that will ultimately contribute to more effective and efficient operations of unmanned data centers, a goal visualized long ago, which has become more pressing to achieve with the global pandemic.

The main limitation to implement them on existing data centers is the lack of adequate instrumentation. However, new technologies such as IoT and sensing devices, wireless communications, and data available directly from the equipment have made the adoption of these trends a reality for many data centers. Artificial intelligence plays a key role in analyzing data, thus providing insights that humans are not capable to decipher. Robotics automation enables to automate processes reducing human error. Humans will always be needed, but adopting these emerging trends will enable faster and better decision making.

Although not directly correlated with automation, there are other important emerging technologies worth exploring in future research, as data centers will greatly benefit from them. One is edge computing, which is about having computing resources near the source of data and having data near where is being required, to reduce latency and data transport costs due to the proximity to the end user. Another is innovative cooling technologies to improve efficiency, namely liquid cooling. Others are storage technology innovations, including making solid state technology more accessible, innovative data protection and security technologies incorporating blockchain technology, and immersive experience, which refers to technologies such as virtual reality, augmented reality and spatial computing.

## References

[1] E. Masanet, A. Shehabi, N. Lei, S. Smith, and J. Koomey, "Recalibrating global data center energy-use estimates," *Science (80-. ).*, vol. 367, no. 6481, p. 984 LP-986, 2020.

[2] U.S. Department of Homeland Security Cybersecurity and Infrastructure Security Agency (CISA), "Guidance on the essential critical infrastructure workforce: Ensuring community and national resilience in COVID-19 response (Mar 28, 2020, Update version 4.0: August 18, 2020)," 2020.

[3] "Telecommunications infrastructure standard for data centers," ANSI/TIA-942-B, 2017.

[4] "Data center design and implementation best practices," ANSI/BICSI 002, 2019.

[5] "Information technology - Data centre facilities and infrastructures. Part 1: general concepts," ISO/IEC TS 22237-1, 2018.

[6] "Information technology - Data centre facilities and infrastructures. Part 2-1: building construction," ISO/IEC TS 22237-2, 2018.

[7] "Information technology - Data centre facilities and infrastructures. Part 3: power distribution," ISO/IEC TS 22237-3, 2018.

[8] "Information technology - Data centre facilities and infrastructures. Part 4: environmental control," ISO/IEC TS 22237-4, 2018.

[9] "Information technology - Data centre facilities and infrastructures. Part 5: telecommunications cabling infrastructure," ISO/IEC TS 22237-5, 2018.

[10] "Information technology - Data centre facilities and infrastructures. Part 6: security systems," ISO/IEC TS 22237-6, 2018.

[11] "Information technology - Data centre facilities and infrastructures. Part 7: management and operational information," ISO/IEC TS 22237-7, 2018.

[12] "Data center site infrastructure tier standard: topology," Uptime Institute, 2018.

[13] "Energy standard for data centers," ANSI/ASHRAE 90.4, 2019.

[14] ASHRAE Technical Committee 9.9, "2011 thermal guidelines for data processing environments – Expanded data center classes and usage guidance," 2011.

[15] ASHRAE Technical Committee 9.9, "Data center networking equipment – Issues and best practices," 2012.

[16] ASHRAE Technical Committee 9.9, "Data center storage equipment – Thermal guidelines, issues, and best practices," 2015.

[17] "Data center operations and maintenance best practices," BICSI 009, 2019.

[18] "Data center site infrastructure tier standard: operational sustainability," Uptime Institute, 2014.

[19] "DCOS - Data Centre Operations Standard," EPI, 2016.

[20] "Green data centres – Part 1: energy and environmental management systems," Singapore Standards SS 564, 2013.

[21] The Senate of the United States. 116th Congress (2019 - 2020), "H.R. 1420. Energy efficient government technology act," 2019.

[22] S. Kent, "Update to data center optimization initiative (DCOI - June 25, 2019). OMB Memorandum M-19-19," 2019.

[23] Ernest Orlando Lawrence Berkeley National Laboratory, "United States data center energy usage report. LBNL-1005775," 2016.

[24] The Green Grid, "PUE™: A comprehensive examination of the metric. White paper # 49," 2012.

[25] M. Levy and J. O. Hallstrom, "A new approach to data center infrastructure monitoring and management (DCIMM)," *2017 IEEE 7th Annual Computing and Communication Workshop and Conference (CCWC)*. Las Vegas, NV, 2017.

[26] M. Levy and J. O. Hallstrom, "A reliable, non-invasive approach to data center monitoring and management," *Advances in Science, Technology and Engineering Systems Journal*, vol. 2, no. 3. pp. 1577–1584, 2017.

[27] M. Levy and D. Raviv, "A novel framework for data center metrics using a multidimensional approach," *15th LACCEI International Multi-Conference for Engineering, Education, and Technology: Global Partnerships for Development and Engineering Education*. Boca Raton, FL, 2017.

[28] M. Levy and D. Raviv, "An overview of data center metrics and a novel approach for a new family of metrics," *Advances in Science, Technology and Engineering Systems Journal*, vol. 3, no. 2. pp. 238–251, 2018.

[29] M. Levy, "A Novel Framework for Data Center Risk Assessment," *2020 11th IEEE Annual Ubiquitous Computing, Electronics & Mobile Communication Conference (UEMCON)*. New York City, NY, pp. 0148–0154, 2020.

[30] K. Bilal, S. U. Rehman Malik, S. U. Khan, and A. Y. Zomaya, "Trends and challenges in cloud datacenters," *IEEE Cloud Computing*, vol. 1, no. 1. pp. 10–20, 2014.

[31] M. Levy, D. Raviv, and J. O. Hallstrom, "Data center modeling using a cyber-physical systems lens," *2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC)*. Las Vegas, NV, 2019.

[32] M. Levy, "Modeling and simulation of data centers to predict behavior," *American Journal of Science and Engineering*, vol. 1, no. 1. pp. 11–20, 2019.

[33] M. Levy, D. Raviv, and J. Baker, "Data center simulations deployed in MATLAB and simulink using a cyber-physical systems lens," *2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC)*. Las Vegas, NV, 2019.

[34] M. Levy, D. Raviv, and J. Baker, "Data Center predictions using MATLAB machine learning toolbox," *2019 IEEE 9th Annual Computing and Communication Workshop and Conference (CCWC)*. Las Vegas, NV, 2019.

[35] R. Evans and J. Gao, "DeepMind AI Reduces Google Data Centre Cooling Bill by 40%," *Deepmind Blog Post*, 2016. [Online]. Available: https://deepmind.com/blog/article/deepmind-ai-reduces-google-data-centre-cooling-bill-40. [Accessed: 25-Oct-2020].

[36] Future Facilities, "Data Center Digital Twin." 2020.

[37] A. Rasheed, O. San, and T. Kvamsdal, "Digital twin: values, challenges and enablers from a modeling perspective," *IEEE Access*, vol. 8, pp. 21980–22012, 2020.

[38] K. M. Alam and A. El Saddik, "C2PS : A digital twin architecture reference model for the cloud-based cyber-physical systems," *IEEE Access*, vol. 5, pp. 2050–2062, 2017.

[39] J. Nelson, J. Connell, and J. Lenchner, "Data center asset tracking using a mobile robot," *ACM SIGMETRICS / international conference on measurement and modeling of computer systems*. Pittsburgh, PA, pp. 339–340, 2013.

[40] W. Choi, K. Park, and K. H. Park, "SCOUT: Data center monitoring system with multiple mobile robots," *The 7th International Conference on Networked Computing and Advanced Information Management*. IEEE, Gyeongju, South Korea, pp. 150–155, 2011.

[41] S. Rosa *et al.*, "An application of laser-based autonomous navigation for data-center monitoring.," in *Intelligent Autonomous Systems 13. Advances in Intelligent Systems and Computing*, 2016, pp. 95–107.

[42] S. Rosa, L. O. Russo, and B. Bona, "Towards a ROS-based autonomous cloud robotics platform for data center monitoring," in *2014 IEEE Emerging Technology and Factory Automation (ETFA)*, 2014, pp. 1–8.

[43] L. Russo, S. Rosa, M. Maggiora, and B. Bona, "A novel cloud-based service robotics application to data center environmental monitoring," *Sensors*, vol. 16, no. 8, p. 1255, 2016.

[44] C. Mansley, J. Connell, J. Lenchner, J. O. Kephart, S. Mcintosh, and M. Schappert, "Robotic mapping and monitoring of data centers," *2011 IEEE International Conference on Robotics and Automation*. IEEE, Shanghai, China, pp. 5905–5910, 2011.

[45] J. Lenchner, C. Mansley, J. Connell, S. Mcintosh, and J. O. Kephart, "Towards data center self-diagnosis using a mobile robot," *8th International Conference on Autonomic Computing*. Karlsruhe, Germany, pp. 81–90, 2011.

[46] B. Kehoe, S. Patil, P. Abbeel, and K. Goldberg, "A survey of research on cloud robotics and automation," *IEEE Transactions on Automation Science and Engineering*, vol. 12, no. 2. pp. 398–409, 2015.

[47] L. S. Terrissa, S. Ayad, and N. Zerhouni, "Robotics based solution for data center e-monitoring," *2019 International Conference on Advanced Systems and Emergent Technologies*. IEEE, Hammamet, Tunisia, pp. 201–208, 2019.

[48] "Switch Sentry. Autonomous security robots." [Online]. Available: https://www.switch.com/switch-sentry/. [Accessed: 22-Dec-2020].

[49] P. Bornet, J. Wirtz, and I. Barkin, *Intelligent Automation*. 2020.

[50] Google AI Blog, "Towards a Conversational Agent that Can Chat About…Anything," 2020. [Online]. Available: https://ai.googleblog.com/2020/01/towards-conversational-agent-that-can.html. [Accessed: 19-Nov-2020].