

**UTILIZATION OF A 3D CFD MODEL TO SIMULATE AIRFLOW
BEHAVIOUR TOWARDS OPTIMIZATION OF
COOLING WITHIN DATA CENTER**

BY

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19/U/GMEM/18804/PD

**A DISSERTATION SUBMITTED TO THE DIRECTORATE OF RESEARCH
AND GRADUATE TRAINING IN PARTIAL FULFILMENT OF THE
REQUIREMENTS FOR THE AWARD OF THE DEGREE OF
MASTER OF SCIENCE IN ADVANCED MANUFACTURING
SYSTEMS ENGINEERING DEGREE OF
KYAMBOGO UNIVERSITY**

OCTOBER, 2024

DECLARATION

I, Ochan Patrick Awoii, candidate for the Masters of Science in Advanced Manufacturing Systems Engineering Degree of Kyambogo University declare that this dissertation is my original work and has never been presented for a degree in any other university. No part of this dissertation is plagiarized work.

Sign. Date.

APPROVAL

This dissertation entitled “*Utilization of a 3D Computational Fluid Dynamics Model to Simulate Airflow Behaviour Towards Optimization of Cooling within Data Center.*”, prepared and submitted by Ochan Patrick Awoii in partial fulfillment of the requirements for the Masters of Science in Advanced Manufacturing Systems Engineering Degree of Kyambogo University, has been supervised and is ready for Submission.

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Dr. Kangwagye Samuel

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Dr. Mukasa Perez

DEDICATION

I dedicate this dissertation to my family members, for their unwavering support and understanding throughout this endeavor, and to all individuals and institutions who contributed to the completion of this thesis, your support is greatly appreciated.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my supervisors, Dr. Kangwagye Samuel and Dr. Mukasa Perez, for their unwavering support, guidance, and encouragement throughout my thesis. Their expertise, patience, and dedication have been invaluable in shaping this research. I am also immensely grateful to the Dean of the Faculty of Engineering for ensuring the smooth running of this research project. Your administrative support has been instrumental in facilitating the progress of my work. A special thank you goes to the Head of the Department of Mechanical and Manufacturing Engineering for the immense support provided to this program. I want to thank my dear brother Okello McDonald Awoii and the rest of the family members for their unwavering support and understanding throughout this endeavor. Finally, I would like to acknowledge the contributions of all individuals and institutions who have played a small role in completing this thesis. Your support has been greatly appreciated. Thank you all for your support, encouragement, and belief in me.

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ACRONYMS

ASHRAE	American Society for Heating, Refrigerating and Air Conditioning Engineers
CAC	Cold Aisle Containment
CFD	Computational Fluid Dynamics
CRAC	Computer Room Air Conditioning
HACA	Hot Aisle / Cold Aisle
HVAC	Heating, Ventilation and Air Conditioning
HWU	High Wall Unit
ICT	Information and Communication Technology
IT	Information Technology

ABSTRACT

In recent years, efficient cooling management systems in data centers have been a high priority to ensure that the optimum operating condition is maintained under the current high level of digitalization. However, numerous data centers still encounter cooling inefficiencies due to factors such as CRAC unit arrangement, poorly positioned perforated tiles, and inadequate return air patterns where supply air mixes with return air. Addressing these challenges is essential for enhancing airflow and improving cooling efficiency. Therefore, in this research, the quality of temperature distribution and the airflow pattern in the DFCU data center were analyzed using the computational fluid dynamics (CFD) approach. CFD simulations were used to quantify the facility's thermal cooling by developing a graphical user interface for component description and viewing. There was a need to compare the flow field and temperature distribution in the data center under different layouts since using CFD models describing solid bodies with thermal mass and energy balance principle makes it possible to visualize temperature and airflow patterns. From the results, the DFCU Bank data center showed temperature variations; hence there was a timely need for efficient cooling management to ensure the temperatures were within the limits recommended by ASHRAE. The simulation results had projections of the high-temperature zones and a comprehensive 3D examination of airflow distribution, and optimization methods established the best airflow arrangement. In addition to that, detailed temperature examinations of the individual racks and three-dimensional thermal mapping would establish the problematic regions and also inform how well the computer room air conditioning units were working. The various conclusions drawn from the research reveal that the cooling capacity would be improved, by adding two additional CRAC units each of 18kw, incorporating a return air duct system for better air distribution, and reducing exhaust air and supply air mixing through arterial blanking. These would result in a streamlined airflow in the data center, and a high cooling efficiency will be noted, which would eventually lead to low levels of energy consumed.

Keywords: Airflow; Cooling efficiency; Thermal mapping; Air distribution

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Global companies and their operations have been revolutionized by Information Technology (IT) (Luftman et al., 1993). The data center, which provides capabilities for data transmission, networking, administration, backup, and storage, is the cornerstone of any commercial corporation (Capozzoli & Primiceri, 2015). These hubs serve as the foundation for the management, processing, and sharing of digital data. Numerous internet services rely on the data center as their base (Uddin & Rahman, 2012). Data centers are essential infrastructures for processing and storing digital data. They require a lot of energy, with cooling accounting for around 45% of the total electrical energy used (Bose et al., 2021).

Recent requirements for data centers revolve around the adoption of smaller servers, denser power configurations, and a steadfast commitment to energy efficiency, reflecting a broader industry shift towards optimizing resource utilization and mitigating environmental impact (Uddin & Rahman, 2010). Meeting the cooling requirements of a data center involves addressing challenges related to high power density, energy efficiency, scalability, redundancy, environmental impact, and regulatory compliance (Schmidt et al., 2005). By carefully considering these factors during the design process, data center operators can ensure their cooling infrastructure's reliability, efficiency, and sustainability. Efficient air distribution, cooling, and thermal management systems are essential components of a well-designed data center infrastructure (Xu et al., 2023). By implementing advanced technologies, integrating systems logically, and prioritizing energy efficiency and environmental sustainability, data center operators can effectively meet the rigorous demands of modern computing

environments while ensuring reliable operation and minimizing operational costs (Thakre et al., 2023). The layout and placement of racks, along with the design and operation of cooling systems, significantly impact air distribution and thermal management within data centers. By carefully considering factors such as rack density, airflow obstruction, cooling system integration, airflow management devices, and scalability, data center operators can optimize cooling efficiency, minimize energy consumption, and ensure reliable operation of critical IT infrastructure (Catulli & Fryer, 2012).

Several strategies were available for improving airflow in data centers, such as hybrid cooling systems, which combine liquid and air cooling to produce a cooling solution that is more effective and efficient (Khalaj & Halgamuge, 2017). The implementation of Hot Aisle/Cold Aisle Containment systems, which involve segregating hot and cold aisles using containment measures such as curtains, doors, or panels, has been shown in studies to significantly enhance cooling efficiency within data centers by preventing the mixing of air streams. This strategy effectively optimizes airflow management, thereby addressing heat dissipation challenges and contributing to the overall effectiveness of data center cooling systems (Martin et al., 2007).

Through experimentation using real-world data and simulations, the research demonstrated how precision cooling systems dynamically adjust airflow and temperature based on actual demand, effectively optimizing energy usage and ensuring ideal operating conditions within the data center. Additionally, the research explores the benefits of strategically arranging racks and servers to promote uniform airflow, minimize hot spots, and facilitate efficient heat dissipation. Results indicate significant

improvements in cooling efficiency and overall performance, highlighting the importance of these strategies in modern data center management (Cho & Kim, 2021).

An essential component of keeping the data center's cooling system functioning properly was cooling management. More than half of all cooling inefficiencies in data centers were caused by inadequate airflow control, per research conducted by the Uptime Institute (Brill, 2007). The study also discovered that cooling energy usage may be lowered by up to 50% by putting appropriate cooling management systems into practice. The complicated structure of airflow patterns makes it difficult for traditional approaches to forecast and improve cooling efficiency. According to a study on airflow management in data centers, it was concluded that using CFD simulation tools is essential for better cooling efficacy, informed decision-making, and effective airflow control (Song et al., 2013).

This research investigated the application of Computational Fluid Dynamics (CFD) simulation in enhancing airflow and, consequently, cooling efficiency at the DFCU data center.

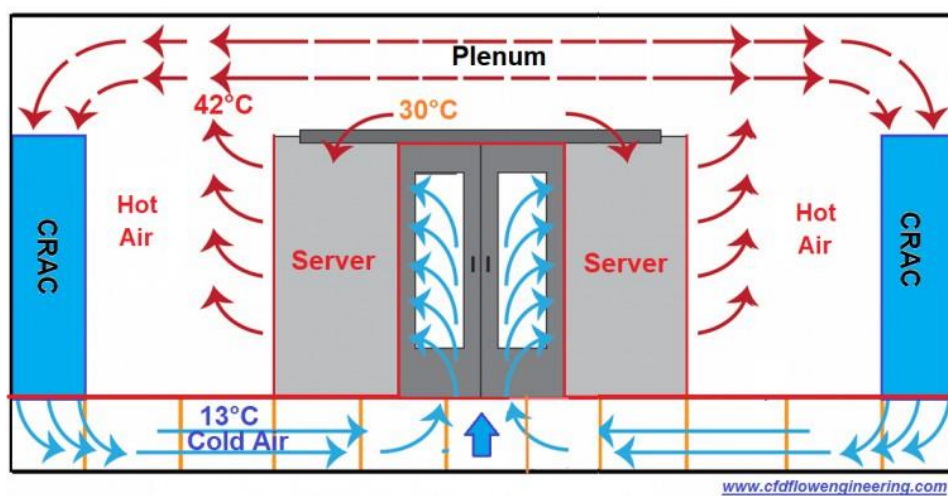


Figure 1. 1: Example of a typical Data Center (www.cfdflowengineering.com)

1.2 General Layout of Data Center

In general data centers use Computer Room Air Conditioning (CRAC) units. Two types of CRAC units are commonly used, the UP-BLOW and DOWN-BLOW types. The Up-Blow CRAC unit blows its cold air upward into the data center cooling space, The Down-Blow type on the other hand blows its air down the raised floor, and to the data center cooling space through the perforated tiles or supply grills. Figure 1.1 illustrates Down-Blow CRAC Units. The CRAC units were installed overhead and discharged cool air downwards towards the floor. The airflow pattern was designed to create a cold aisle/hot aisle configuration in the data center. The cold air was delivered under the raised floor and through perforated tiles into the cold aisle, then directed up through the servers' front intake to cool them. After absorbing heat from the servers, the air becomes warmer and rises, exiting through the servers' rear exhaust into the hot aisle. From there, it returns to the CRAC units for cooling through the plenum.

1.3 Description of the Data Center Under Study

1.3.1 DFCU Data Center Layout

The study was conducted at DFCU Bank's main branch data center. The layout of the air conditioning is illustrated in Figure 1.2. The Data Center occupies 31 sq.m of space on the second floor of DFCU Towers on Plot 26, Kyadondo Rd., Nakasero. The Data Center has no windows, no walls exposed directly to the sun, is separated from the UPS room with a wall of insulating foam and is provided with an airlock separating it from the main office areas. The Data Center contains 8no. IT racks each dimension (LxWxH) 0.6 X

1.066 X 1.867 with space available for an extra 4no. racks. The eight racks were installed in two rows with two, Rack 07 of power capacity 7611W and Rack 08 of

power capacity 4116W on one side. The other row has six racks of power capacity, Rack 01-6713W, Rack 02-11960W, Rack 03-1825, Rack 04-11898.7, Rack 05-10664, and Rack 06-8950W. There

are two air-cooled Computer Room Air Conditioning (CRAC) units of 18kW each and of dimension (LxWxH) of 0.8m x 0.6m x 1.94m, and two Samsung High Wall Units (HWU) of 7kW each giving a total cooling capacity of 50kW. The CRAC units supply air through 8no. floor grills of dimension 0.6m x 0.6m and 4no. of perforated tiles of dimension 0.6m x 0.6m Return air is not ducted. No physical barriers are separating the hot and cold aisle of both rows of racks.

1.3.2 DFCU Data Center Thermal Mapping Discrepancy

Effective cooling management systems are vital for preserving ideal operating conditions in the world of data centers. The industry-recognized ASHRAE guidelines state that a classic raised floor data center with Computer Room Air Conditioners (CRAC) should operate in a temperature range of 18 to 27⁰C. This range is essential for maintaining the cooling infrastructure's dependability and efficiency since it promotes the steady operation of vital components and guards against malfunctions brought on by overheating. Figure 1.3 illustrates the thermal mapping at the DFCU data center. Inside DFCU data center's Hot Aisle, which runs from the rear of Racks 01 to 06, has an average temperature of about 26⁰C. The two High Wall Air Conditioning units have been installed to reduce exhaust heat from these racks; nevertheless, these units also contribute negatively by recirculating the exhaust heat into the Cold Aisle, raising the temperature of supply air. As a result, the air supply from the two DFCU CRAC units causes the average supply temperature in the Cold Aisle, which is located between the two rows of racks 01 to 06 and Racks 07 and 08, to be around 22⁰C instead of the

expected temperature of 16-degree Celsius. Interestingly, the average temperature behind Racks 07 and 08 increases to 29°C mainly because of the exhaust heat released by these Racks.

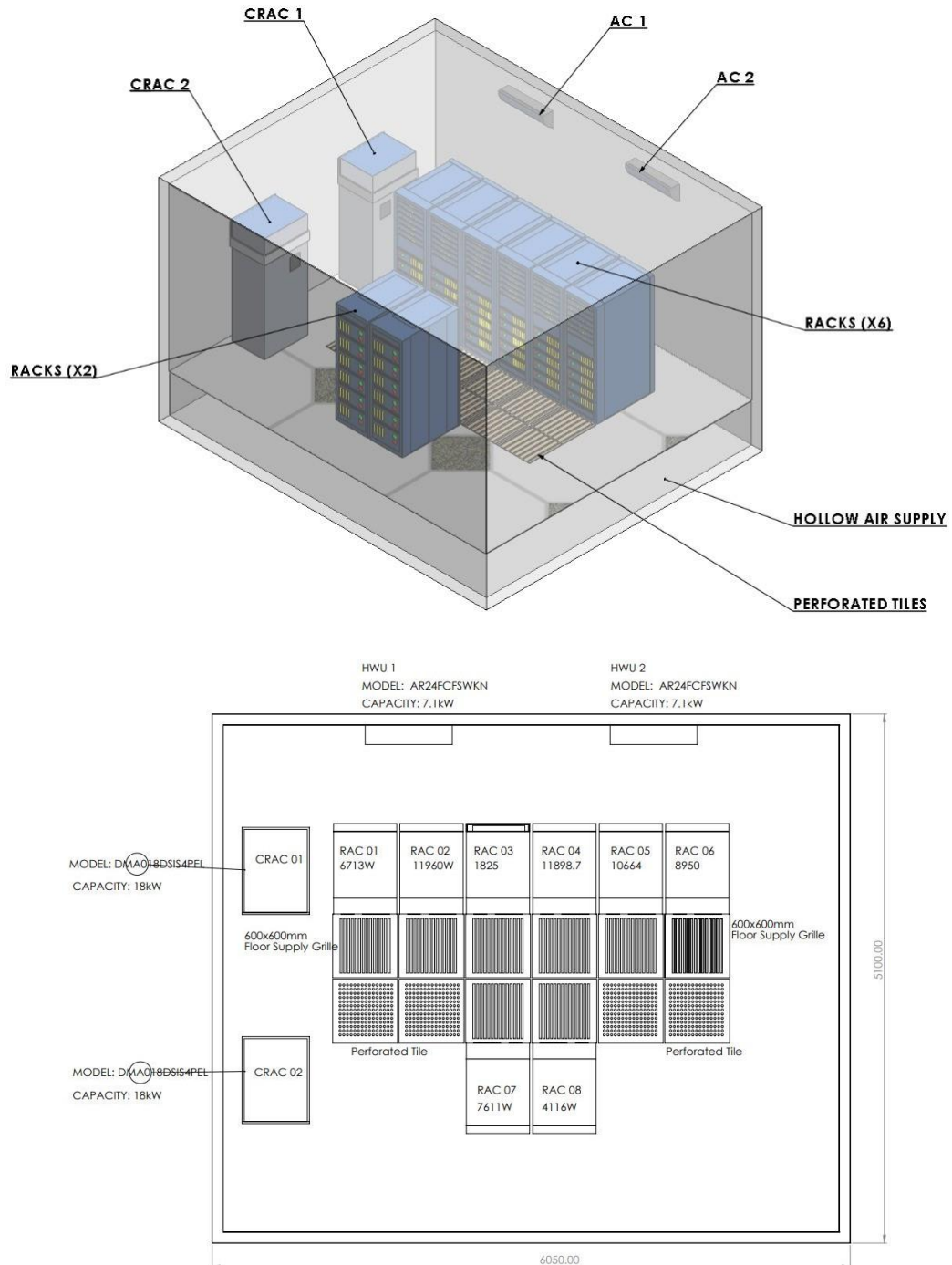


Figure 1.2: The existing DFCU data center showing CRAC Units, racks and perforated tile layout. A 3-D view in the top figure and a plan view in the bottom figure.

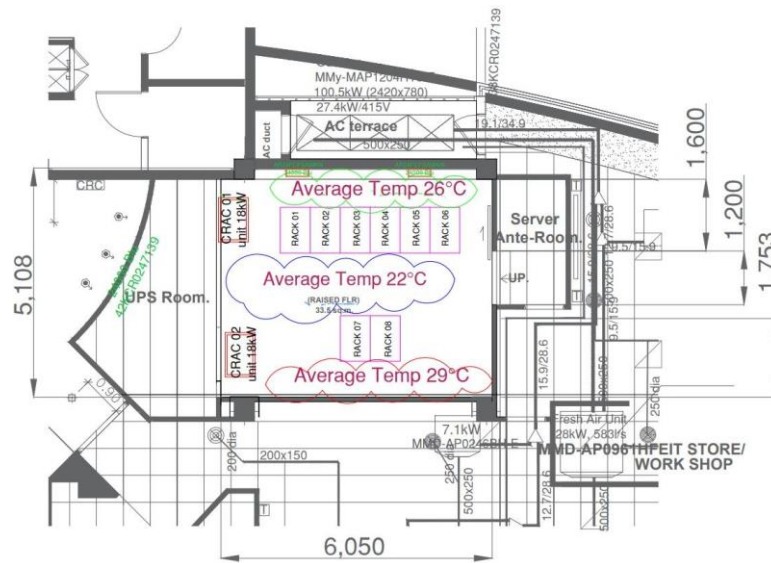


Figure 1.3: A section front view of Figure 1.2 showing the thermal mapping

1.4 Problem Statement

Significant temperature variations are occurring at DFCU Bank’s data center, with reported temperatures ranging from as low as 19°C to as high as 30°C. This disparity is an indication of poor airflow such as the mixing of supply air from the CRAC units with exhaust heat from the Racks. These changes significantly hamper the operational effectiveness of the data center. Operating below the advised temperature range puts stress on cooling systems and increases the possibility of over-cooling delicate equipment, which might result in moisture-related issues and decreased functionality. On the other hand, temperatures over this threshold may cause overheating of the equipment, premature aging of the system, and system failures, which might endanger the dependability and accessibility of critical services. Therefore, these uneven temperature distributions must be addressed to guarantee the best possible performance and long-term viability of the data center architecture.

1.5 Research Objectives

1.5.1 Main Objective

To utilize a 3D CFD model to simulate airflow behavior towards optimization of cooling within the DFCU data center.

1.5.2 Specific Objectives

The Specific Objectives are:

- i) To analyze current airflow patterns within the DFCU Bank Data Center.
- ii) To identify areas of inefficiency in the cooling system through thermal mapping simulation of the existing data center.
- iii) To optimize airflow for improved cooling efficiency through Simulation Using an Optimized 3D Mode.

1.6 Justification of the Study

The DFCU data center currently faces a significant challenge with limited cooling due to insufficient airflow. Data centers generate substantial heat, making effective cooling systems essential to maintain appropriate temperature and humidity levels. Optimizing these cooling systems is important as they consume a significant amount of energy. Enhancing the cooling efficiency can lead to considerable reductions in energy consumption and operational costs.

This research aims to contribute to the existing body of knowledge on data center management. By utilizing a 3D Computational Fluid Dynamics (CFD) model to simulate airflow behavior, this study seeks to optimize cooling within the DFCU data center, addressing the current limitations and improving overall efficiency.

1.7 Scope of the Study

1.7.1 Time Scope

This research was conducted within the time frame of eight months, starting with a preliminary research review to identify gaps in data center cooling optimization strategies. Data was gathered and analyzed to identify factors affecting airflow behavior and efficiency. A computer model was developed to replicate airflow behavior in data centers, and simulations were conducted to verify predictions.

1.7.2 Content Scope

The research examined the significance of airflow management and cooling optimization in data centers, emphasizing the vital role these factors played in enabling technological progress. It went over the body of research on cooling optimization techniques and simulation models, described the steps involved in gathering data, and created an optimization model specific to the needs of the data center. After that, a simulation was run through the model to see how well it performed in enhancing data center efficiency. A thorough report outlining the results highlighted the effects of various optimization scenarios on data center operations. Recommendations for the best airflow and cooling options for the DFCU Data Center were provided in the study's conclusion.

1.7.3 Geographical Scope

The research was conducted at DFCU Bank's main branch data center. The Data Center occupied 31 sq.m of space on the second floor of DFCU Towers on Plot 26, Kyadondo Rd., Nakasero, Kampala Uganda. The Data Center contains 8no. IT racks two air-cooled Computer Room Air Conditioning (CRAC) units of 18kW each and

two Samsung High Wall Units (HWU) of 7kW each giving a total cooling capacity of 50kW. This data center serves the entire DFCU Bank branches all over the Country.

1.7.4 Chapter Summary

Chapter One introduces the study, emphasizing the importance of data centers in IT infrastructure and the need for optimal layout for efficiency. It details the DFCU Data Center's layout and thermal mapping issues. Chapter Two reviews the literature on heat load sources, cooling methods, and energy consumption, highlighting the role of CFD in optimizing cooling. Chapter Three outlines the methodology, including data collection, cooling system evaluation, and airflow optimization strategies. Chapter Four presents results and discussions on cooling patterns, thermal mapping, and the effectiveness of proposed optimizations. Chapter Five summarizes the findings, conclusions, and recommendations, emphasizing improved cooling efficiency and reduced hotspot

CHAPTER TWO: LITERATURE REVIEW

2.1 Sources of Heat Load at Data Centers

There are several sources of heat load in a data center that can contribute to increased energy consumption and reduced efficiency. These sources can be divided into two categories: internal and external.

Internal sources of heat load include the servers, storage devices, and networking equipment within the data center. These devices generate heat as a byproduct of their operation and can contribute significantly to the overall heat load of the data center.

One study found that servers in a data center can generate up to 90% of the total heat load (Cho et al., 2015). The number and size of these devices can significantly impact the heat load, with larger servers and more servers requiring more energy to cool.

External sources of heat load include the ambient temperature and humidity of the surrounding environment, as well as the heat generated by people and other equipment in the vicinity of the data center. These external sources can contribute to the overall heat load and increase the demand for cooling systems in the data center. Another study also found that high ambient temperatures and humidity can significantly increase the heat load in a data center and reduce the efficiency of the cooling systems (Xu et al., 2023).

One source of heat load is the IT equipment itself, including servers, storage systems, and networking equipment (Q. Zhang et al., 2021). These devices generate heat as a byproduct of their operation, and the amount of heat generated is directly related to the power consumption of the equipment (Zhu et al., 2023).

Another source of heat load is the lighting and electrical systems in the data center. These systems also generate heat as a byproduct of their operation, and the amount of heat generated is related to the power consumption of the systems (Gao et al., 2016). Additional sources of heat load include people working in the data center (Shuja et al., 2016). Humans generate heat through metabolism, and the number of people in the data center can significantly contribute to the overall heat load (Bilal et al., 2014).

External factors such as ambient temperature and humidity can also contribute to the heat load in a data center. Higher ambient temperatures and humidity levels can increase the cooling load in the data center (Rong et al., 2016).

The sources of heat load in a data center include IT equipment, lighting, electrical systems, people, and external factors such as ambient temperature and humidity. Proper management of these sources can help to ensure efficient cooling and energy use in the data center.

2.1.1 Different Cooling Methods at Data Centers

There are several approaches to cooling data centers, including air-based, liquid-based, and hybrid systems. Air-based cooling systems use air to cool the data center by drawing in outside air or circulating air within the facility. This can be achieved through the use of air conditioning units, fans, and other mechanical systems. One advantage of air-based cooling is that it is generally less expensive to install and maintain compared to liquid-based systems (Mukherjee et al., 2020).

However, air-based cooling can be less effective at removing heat from the data center, particularly in hot and humid environments (H. Zhang et al., 2014). Liquid-based cooling systems, on the other hand, use a liquid, such as water or a water-glycol

mixture, to transfer heat away from the data center. This can be achieved through the use of chillers, cooling towers, and other mechanical systems. Liquid-based cooling can be more effective at removing heat from the data center compared to air-based systems, particularly in high-density environments (Rubenstein et al., 2010). However, liquid-based cooling can be more expensive to install and maintain compared to air-based systems (Lu et al., 2018).

2.1.2 Energy Consumption at Data Centers

Data centers are known for their high energy consumption, with a significant portion of that energy being dedicated to heating, ventilation, and air conditioning (HVAC) systems. These systems play a crucial role in maintaining optimal temperature and humidity levels within the data center to ensure the proper functioning of electronic equipment. As such, understanding and addressing the energy usage trends of data center HVAC systems is essential for reducing overall energy consumption and improving the efficiency of these facilities.

One study found that HVAC systems account for approximately 40% of the total energy consumption in data centers (Ni & Bai, 2017). This trend is expected to continue as data centers continue to grow in size and complexity, making it necessary to implement energy-efficient HVAC solutions. One approach to reducing energy consumption in data centers is the use of variable air volume systems, which allow for more precise temperature and humidity control compared to traditional constant air volume systems (Huang & Masanet, 2015). Variable Air Volume systems have been shown to significantly reduce energy consumption in data centers, with some estimates suggesting energy savings of up to 50% (Q. Zhang et al., 2021).

Another trend in data center HVAC energy usage is the adoption of renewable energy sources. With a greater emphasis on sustainability and lowering carbon emissions, data centers are turning to renewable energy sources like solar and wind power to power their HVAC systems (Oró et al., 2015). These renewable energy sources can provide a significant portion of the energy needed to run data centers, reducing the reliance on fossil fuels and reducing greenhouse gas emissions. Saving energy in data centers is important for several reasons. Firstly, data centers consume a significant amount of energy, and their energy usage is expected to continue to increase in the future (Zakarya, 2018). This increase in energy consumption has both financial and environmental consequences.

In terms of financial consequences, the cost of energy for data centers can be significant and is likely to continue to rise in the future (Masanet et al., 2020). Therefore, reducing energy consumption in data centers can lead to cost savings for the companies that operate them.

In terms of environmental consequences, data centers contribute to carbon dioxide emissions and other environmental impacts through their energy usage (Coroama & Hilty, 2014). As such, reducing energy consumption in data centers can help to reduce their environmental impact and contribute to efforts to mitigate climate change.

There are also other benefits to saving energy in data centers. For example, reducing energy consumption can lead to more efficient and reliable operation of the data center (Chen et al., 2014). Additionally, implementing energy-saving measures in data centers can also help to reduce the risk of power outages and improve the overall resiliency of the data center (Isazadeh et al., 2023).

Saving energy in data centers is important for financial, environmental, and operational reasons. There are many ways to save energy in data centers, including implementing energy-efficient technologies and practices, and these efforts can lead to cost savings, reduced environmental impact, and improved data center performance

2.1.3 Airflow at Data Centers

Over the years, researchers have conducted various studies to investigate airflow dynamics and identify strategies to optimize the cooling performance in data centers. One study explored the use of Hot Aisle/Cold Hisle (HACA) configurations in data centers, which involves arranging server racks in alternating rows with the front-facing one aisle and the back facing another aisle. The researchers found that HACA significantly improved the airflow and temperature distribution in the data center, resulting in a 20% reduction in cooling energy consumption (Arghode & Joshi, 2016).

Another study investigated the impact of raised floor designs on airflow in data centers. The researchers conducted experiments with various perforated tile designs and under-floor plenum configurations. They found that an optimized design could significantly improve the cooling efficiency and reduce the pressure drop across the raised floor (Jin et al., 2019).

Recently, an experimental study on the effectiveness of cold aisle containment (CAC) in a data center was conducted. Their results showed that CAC can improve the airflow and temperature distribution, especially at high server loads, and the positioning of the perforated tiles and barrier configuration can significantly impact the cooling findings can inform the design and operation of data centers to improve energy efficiency and reduce costs (Lee et al., 2022).

2.1.4 Factors Affecting Airflow at Data Centers

Several factors affect the airflow in data centers, including the layout of the racks, cooling system design, server power density, and the position of perforated tiles. In this section, we examined some recent studies that have investigated these factors' impact on the airflow in data centers.

Nada and Said (2017) demonstrated that the hot-aisle containment system was more effective in reducing the server inlet temperature than the cold-aisle containment system. Additionally, they showed that rearranging the racks could improve the airflow distribution and reduce the temperature variation.

Abbas et al. (2021) on the other hand concluded that the server power density had a significant impact on the cooling efficiency, with higher-density servers resulting in more hot spots and reduced airflow. The study suggested that a more comprehensive cooling system design could mitigate the adverse impact of higher power density servers.

Additionally, Chu and Wang (2019) evaluated the impact of perforated tile position on the airflow and cooling performance in a data center. They found that the perforated tile position had a significant impact on the airflow distribution and cooling efficiency. The study suggested that optimizing the perforated tile position could improve the cooling efficiency of the data center.

Finally, Lu and Zhang (2020) agreed with the earlier finding by Nada and Said (2017). They found that the hot aisle containment system was the most effective in reducing the server inlet temperature and improving cooling efficiency. By optimizing these

factors, it is possible to improve the cooling efficiency and reduce energy consumption in data centers.

2.1.5 The Importance of Computational Fluid Dynamics (CFD) in Predicting Airflow Patterns

Computational Fluid Dynamics (CFD) codes are increasingly used to forecast airflow patterns and temperature distributions in data centers, providing valuable insights into complex thermal dynamics (Athavale et al., 2018). Validation against empirical data enhances the credibility of these simulations, enabling the development of efficient cooling strategies (Kang et al., 2001)

Firstly, Jin et al. (2019) provide a comprehensive review emphasizing the pivotal role of CFD simulations in understanding airflow dynamics within data centers, emphasizing its impact on optimizing cooling efficiency and energy sustainability.

Similarly, Shahsavari et al. (2023) focus on validating CFD models for airflow prediction within data centers, stressing the importance of accurate simulation techniques in optimizing cooling strategies and thermal management.

Additionally, Mandadi (2022) discusses various CFD modeling approaches used to simulate airflow distribution in data centers, underlining their significance in predicting and optimizing cooling performance.

Furthermore, Zakarya (2018) employs CFD simulations to investigate airflow distribution within data centers numerically, demonstrating its utility in optimizing airflow management strategies and reducing energy consumption.

Finally, Thakre et al. (2023) highlight the application of CFD modeling in optimizing cooling performance in data centers, emphasizing its role in predicting airflow patterns and enhancing thermal management strategies. Collectively, these studies highlighted the critical importance of CFD in understanding and improving airflow dynamics within data centers, offering insights into optimizing cooling efficiency and enhancing energy sustainability in such environments.

2.1.6 Summary of Research Gap

Data centers face cooling inefficiencies due to inadequate airflow control. Over 50% of these inefficiencies result from poor airflow management. Implementing effective cooling management systems can reduce cooling energy usage by up to 50%. Traditional approaches struggle to predict and enhance cooling efficiency due to complex airflow patterns. Utilizing Computational Fluid Dynamics (CFD) simulation tools is essential for informed decision-making, better cooling efficacy, and effective airflow control.

The research aims to enhance cooling efficiency at the DFCU data center through CFD simulation

CHAPTER THREE: METHODOLOGY

3.1 Analyzing Current Airflow Patterns within the DFCU Bank Data Center

3.1.1 Data Collection and Tools Used

The data collected for analyzing the current airflow patterns at the existing DFCU Bank Data Center included the dimensions of the data center (length, width, and height), which were essential for developing a simulation model. Additionally, the dimensions, capacity, and placement of the CRAC units and HWU units were recorded, along with the fan flow rates for both cooling units and server racks. The load capacity of the server rack space, the arrangement of perforated tiles, and the temperature distribution within the data center were also documented. This comprehensive data set was utilized to formulate a methodology for the first objective of the study. The technical details of this data center are discussed in Section 1.3.

The tools required for data collection included a laser distance meter and tape measure for measuring the data center dimensions, manufacturer specifications, and flow meters for obtaining details and measuring airflow rates of the CRAC and HWU units, rack specifications, tile layout plans, anemometers for measuring airflow through perforated tiles, and temperature sensors and data loggers for monitoring and recording temperature distribution within the data center.

3.1.2 Review and Appraisal of Existing Cooling System Installation and Design

The current cooling system's installation and design were evaluated and reviewed to ensure that they adhered to the following checklist, which is detailed below. During the data-gathering process, every item had a physical inspection, from which an analysis was conducted to determine the present functioning of the CRAC systems. Data was gathered to identify the system's critical performance metrics and the current heat loads

that are influencing the interior climate of the data center. To obtain insight into the functioning of the systems, installation/as-built drawings and a conversation on the performance of the current system with the contact person were used. The checklist meeting ASHRAE Standard 90.4-2016: Energy Standard for Data Centers served as the foundation for the conclusions and recommendations, which recommended optimization techniques.

1. CRAC capacity checks: Existing CRAC Capacities were checked to ensure that the current power load of the Data Centre was within the bearable capacity of the cooling system. 1W of IT power is equivalent to 1W of cooling. To determine the existing total heating load, the researcher used the total power consumed by the IT equipment operating at 100% capacity as recommended by ASHRAE Standard 90.4-2016.
2. CRAC unit check: The existing CRAC unit was checked for demand fighting to determine if there was uncoordinated CRAC unit operation in opposing modes like humidification and dehumidifying. To check for demand fighting, the airflow and temperature were measured at the floor grills, and the resulting values were compared with the manufacturer's design values and the values displayed on the CRAC unit display interfaces.
3. CRAC unit and Floor grill placement: The CRAC unit and floor grill placement were checked to determine if they were placed by recommended standards.

Checked aisle and rack temperatures: The room temperatures were measured at strategic positions in the aisles, generally centered between equipment rows and (1 meter) above the floor, and the values were compared with the recommended inlet temperatures of the IT equipment manufacturer. Rack

temperature measurements were taken at the center of air intakes and exhausts at the top, middle, and bottom of each rack.

4. Arrangement of floor and aisle tiles and air velocity from floor tiles: Air flow velocity was checked to ensure uniform flow across all floor grilles.
5. Airflow between racks: The airflow between racks was checked for gaps, unused rack spaces, unsealed cable openings, and excess cabling that could have adversely affected airflow through the IT equipment leading to hot spots of stagnant air.
6. Redundancy: The systems were checked for redundant cooling capacity as recommended by ASHRAE.

3.1.3 CRAC Capacity Check

Estimating the current cooling loads required an understanding of the amount of heat produced by the IT equipment and by other heat sources inside the data center. The total cooling requirement was the sum of the heat gains from heat released inside the space – IT equipment, UPS, power distribution, air conditioning units, lighting, and personnel.

1. Building envelope heat from the roof, walls, and windows; load varies with the outdoor environment.
2. Ventilation air load filtered outdoor air and infiltration; load varies with the outdoor environment. The worksheet below Table 3.1 was adopted to determine the total heat output of a data center quickly and reliably. Heat Output estimation was by ASHRAE Standard 90.4-2016: Energy Standard for Data Centers which recommends the following environmental conditions.

3. Dry bulb temperature: 64.4 to 80.6⁰F
4. Dew Point: 41.9 to 59⁰F
5. The absolute humidity of a data center, as measured in grams of water per gram of dry air, should be kept between 0.006 and 0.011. ASHRAE Standard 62, was used to estimate the ventilation air requirement of personnel within the Data Centre. The standard calls for a minimum of 15 CFM per person.

3.2 Identifying Areas of Inefficiency in the Cooling System through Thermal Mapping Simulation.

3.2.1 Review of Collected Data.

The first step in identifying inefficiencies in the cooling system of a data center involves a thorough review of the data collected in Objective One. This data included critical parameters such as temperature, and airflow measurements. By reviewing this data, it was ensured that it was comprehensive and accurately represented the current state of the data center’s cooling system. This step was important because the accuracy of the subsequent analysis and simulations depended on the quality and completeness of the initial data.

Table 3.1: Data Centre AC Cooling Load Estimation Sheet.

ITEM	DATA REQUIRED	HEAT OUTPUT	HEAT OUTPUT TOTAL
IT equipment (Servers, switches, Routers)	Total IT load (sum of the power inputs of all IT equipment)	Q = Same as total IT load power in watts i.e.1kW of cooling per kW of power.	75,172 Watts
UPS with battery	Power system rated power (rating of UPS systems, excluding redundant modules.	Q = 0.04 x power system rating) + (0.06 x total IT load power.	5,590 Watts
Data Centre AC Cooling Load Estimation sheet.	Power system rated	Q = (0.02 x power system rating) + (0.02 x total IT load power)	2,043 Watts
Lighting	Floor area in square feet and total number of lights, converted to watts.	Q = Floor area (sqft) x 2	660 Watts
People	Maximum number of personnel in data centers, converted to watts	Q = Number of people x 100	200 Watts
Total amount of cooling required (Q)			83,465 Watts = 84 kW

3.2.2 Development of the Thermal Mapping Model

Once the data had been reviewed, the next step was to develop a 3D model of the data center. This model was created using the collected data and integrated thermal properties and cooling system parameters. The development of this model involved several sub-steps: first, creating the basic structure of the data center; second, incorporating the thermal properties of the materials and equipment; and third, validating the initial model by comparing it with real-world measurements. This validation ensured that the model accurately reflected the actual conditions in the data center.

3.2.3 Simulation Setup

With the 3D model developed, the next step was to set up the thermal mapping simulation environment using Computational Fluid Dynamics (CFD) software. This involved in putting the 3D model and all relevant parameters into the simulation software. Additionally, the simulation scenarios were defined, which included different operational conditions and cooling strategies. This setup was important for creating a realistic simulation environment that could accurately predict the thermal behavior of the data center under various conditions.

3.2.4 Running Simulations

After setting up the simulation environment, the thermal mapping simulations were run under various scenarios. During these simulations, the temperature distribution, airflow patterns, and other relevant data were recorded. Conducting repetitive simulations was crucial to ensure the consistency and reliability of the results. By running multiple simulations, patterns were identified, and it was verified that the results were not due to random variations or anomalies.

3.2.5 Analysis of Simulation Results

The next step involved analyzing the thermal maps generated from the simulations to identify hotspots and areas of inefficiency. This analysis included comparing the simulation results with the actual performance data to validate the findings. This analysis helped in pointing out specific areas where the cooling system was not performing optimally and provided insights into potential improvements.

3.2.6 Tools and Software

CFD software was particularly used for setting up and running the thermal mapping simulations.

3.2.7 The Boundary Condition Used for Simulation

Table 3.2 shows the boundary conditions used in the simulation of airflow at the data center. These conditions are based on data collected through physical measurements at the DFCU data center, representing real-world data

Table 3.2: Boundary Condition.

S/N	Type	Components			Vector		Symbol	Value
1	Inlet Flow Rate	CRAC1 CRAC4		to	Normal to	Face	Q_{in}	1.43 m ³ /s, Fully developed flow, Temperature: 14°C
2	Outlet Flow Rate	CRAC1 CRAC4		to	Normal to	Face	Q_{out}	1.43 m ³ /s, Fully developed flow, Temperature: 14°C
3	Inlet Flow Rate	HWU1, HWU2			Normal to	Face	Q_{in}	0.31 m ³ /s, Fully developed flow, Temperature: 14°C
4	Outlet Flow Rate	HWU1, HWU2			Normal to	Face	Q_{out}	0.31 m ³ /s
5	Heat Generation Rate	Rack Rack08	01	to	Diffusive		Q_H	Rack01=613W, Rack02=1169W, Rack03=785W, Rack04=1169W, Rack05=785W, Rack06=1169W, Rack07=785W, Rack08=1166W
6	Rack Blower Fan	Rack01 Rack08		to	Through the rack		V_{fan}	0.2 m/s at 40Pa
7	Ambient Conditions	Initial Condition			Global		-	Static Pressure: 101325Pa, Temperature: 26°C

3.3 Optimizing Airflow for Improved Cooling Efficiency through Simulation Using an Optimized 3D Model.

The methodology employed for optimizing airflow and cooling efficiency at the DFCU Data Center involved a systematic approach aimed at improving the efficiency and effectiveness of the existing infrastructure. The first step involved refining the 3D model developed for the existing data center. This refinement included incorporating the proposed additional Computer Room Air Conditioning (CRAC) units, detailing the return ductwork, and accurately positioning the high wall split systems in the Hot

Aisle. The arrangement of the server rack was not altered, while the raised floor pattern and duct layout were updated to reflect the new configuration as shown in Figure 4.10. Following the refinement of the 3D model, the simulation setup was initiated. Computational Fluid Dynamics (CFD) software, was used for the simulation. Boundary conditions, including inlet air temperature, flow rates, and heat loads from the servers, were defined. A fine mesh was generated for the 3D model to ensure accurate simulation results, and initial conditions, such as the initial temperature distribution and airflow patterns, were set.

The simulation was then executed on the updated 3D model. During this phase, the simulation progress was closely monitored, and adjustments were made as necessary to ensure convergence. This step was crucial in obtaining reliable and accurate data for subsequent analysis.

The results of the simulation were thoroughly analyzed. Thermal mapping patterns generated by the simulation were examined, focusing on temperature distribution and hotspots. Airflow patterns were evaluated to identify areas of recirculation or insufficient cooling. The new simulation results were compared with the previous ones to assess improvements in cooling efficiency.

Based on the analysis, any issues or inefficiencies in the current setup were identified. Adjustments to the CRAC units, ductwork, or rack layout were proposed to further optimize airflow and cooling. These proposed adjustments were implemented in the 3D model, and the simulation was re-run to validate the improvements.

Finally, the findings from the simulation were documented. This documentation included detailed thermal maps, airflow patterns, and any proposed adjustments.

Recommendations were provided for implementing the optimized layout in the actual data center, ensuring that the improvements identified through simulation could be effectively realized in practice.

The tools used in this methodology included Computational Fluid Dynamics (CFD) software.

3.3.1 Validation of Optimization

Power Usage Effectiveness (PUE) and Rack Cooling Index (RCI) of the data center were calculated before and after optimization to evaluate the effectiveness of the implemented changes. By comparing these metrics to quantify improvements in energy efficiency and cooling performance. The PUE provided insights into the overall energy consumption relative to the IT load, while the RCI highlighted the effectiveness of the cooling system in maintaining optimal rack temperatures. This analysis helped identify areas of improvement and validate the impact of optimization efforts.

3.4 Governing Equations

3.4.1 Continuity Equation: Ensures mass conservation

$$\frac{\delta \rho}{\delta t} + \nabla \cdot (\rho \mathbf{u}) = 0 \dots\dots\dots (3.1)$$

Where;

ρ): *Density of the air.*

\mathbf{u}): *Velocity vector of the airflow.*

$\nabla \cdot (\rho \mathbf{u})$: *Representing the rate at which mass enters or leaves a control volume.*

3.4.2 Navier-Stokes Equations: Models momentum transfer

$$\rho \left(\frac{\delta u}{\delta t} + u \cdot \nabla u \right) = -\nabla p + \mu \nabla^2 u + F \dots\dots\dots(3.2)$$

Where;

(ρ) : Density of the air.

(u) : Velocity vector of the airflow.

$\left(\frac{\delta u}{\delta t}\right)$: Local acceleration of the airflow.

$u \cdot \nabla u$: Convective acceleration, representing the change in velocity due to the movement of air.

$(-\nabla p)$: Pressure gradient force.

$(\mu \nabla^2 u)$: Viscous forces, where (μ) is the dynamic viscosity of the air.

(F) : External forces acting on the air, such as gravity or fan forces.

3.4.3 Energy Equation: Accounts for heat transfer

$$\rho c_p \left(\frac{\delta T}{\delta t} + u \cdot \nabla T \right) = k \nabla^2 T + Q \dots\dots\dots(3.3)$$

Where;

(ρ) : Density of the air.

(c_p) : Specific heat capacity at constant pressure.

(T) : Temperature of the air.

$\left(\frac{\delta T}{\delta t}\right)$: Local rate of change of temperature.

$(u \cdot \nabla T)$: Convective heat transfer, representing the transport of heat due to airflow.

$(k \nabla^2 T)$: Conductive heat transfer, where (k) is the thermal conductivity of the air.

(Q) : Dissipation function, representing the conversion of mechanical energy into thermal energy

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Assessment of Cooling Pattern at the Data Center

The analysis of the existing DFCU Data Center highlights detailed cooling limitations of the CRAC (Computer Room Air Conditioning) adequacy and operational limitations. The total cooling load of **50 kW** was distributed among 2 CRAC units and 2 High Wall Units (HWU). Each CRAC unit had a capacity of **18 kW**, identified by model number DMA018DSIS4PE1, while each HWU was rated at 7 kW, denoted by model number AR24FCFSAWKN.

Examination showed a total cooling load of **84 kW** from IT equipment, lights, and personnel. Table 3.1 shows the cooling load estimation sheet. This disparity between cooling capacity and heating loads, especially when the data center operates near maximum capacity, indicates an inadequate cooling system. The lack of redundant capacity further exacerbates operational risks, jeopardizing facility resilience and reliability.

The analysis emphasizes the urgent need for strategic interventions to rectify the imbalance between cooling capacity and heating loads at the DFCU Data Center.

4.2 Simulation Results Recorded for the Existing Data Center indicating Areas of Cooling Inefficiency

The computational fluid dynamics (CFD) simulation of the model shown in Figure 1.2 yielded critical insights into the thermal dynamics within the data center. This comprehensive analysis included the examination of temperature clouds, room and rack thermal maps, and their direct impact on CRAC performance, return temperatures, and thermal maps throughout the facility.

Figures 4.1 through 4.9 illustrated the thermal profiles observed at various planes within the data center, focusing on both room and rack temperatures. With two CRAC units in operation, a total airflow of 1.708 m³/sec was measured.

4.2.1 Thermal Map Recorded at 1m and 2m Above the Raised Floor

Thermal profiles were specifically captured at heights of 1m height and 2m height above the floor, as shown in Figures 4.1 and 4.2. The analysis reveals no significant temperature rise at the higher elevation of 2m compared to the lower elevation of 1m, particularly evident at the end rack of the data center. Notably, the thermal profiles highlight the mingling of supplied cold air with heated exhaust air within the cold aisle, particularly noticeable around Racks 7 and 8. This phenomenon increases the intake temperatures of the racks, surpassing the supply temperature.

The airflow pattern, predominantly directed from vent tiles into the cold aisle and subsequently through server inlets and exits, contributes to the transfer of heated air to the room's sidewalls and ultimately to the CRAC units.

These localized areas of elevated temperatures pose a significant risk to the reliability of computer components, underscoring the critical importance of employing effective cooling solutions to maintain temperatures within optimal ranges.

The simulation results underscore the intricate interplay between airflow patterns and temperature distributions within the data center environment.

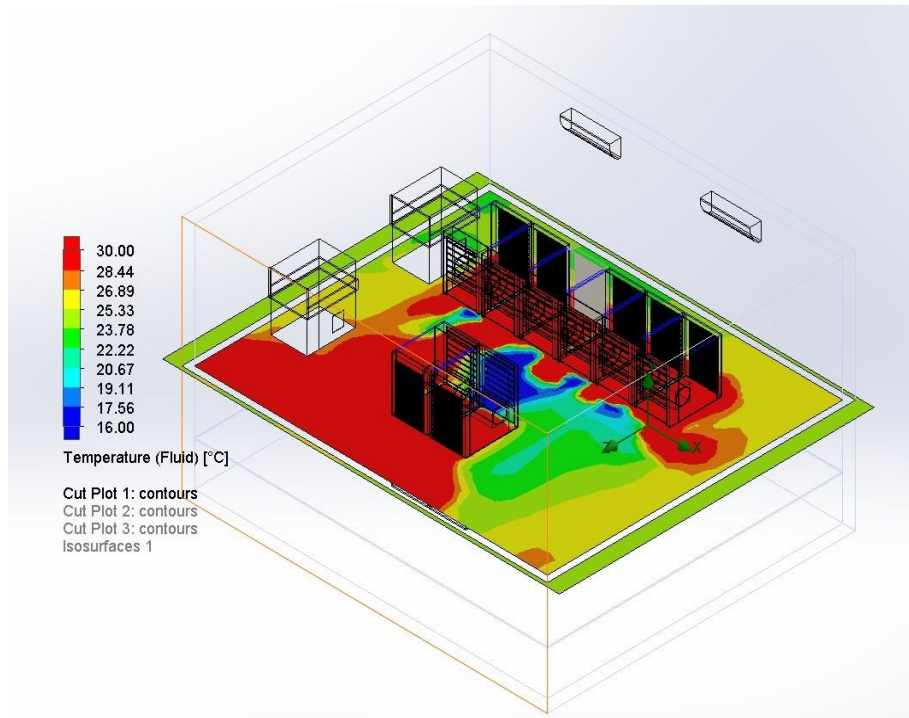


Figure 4.1: Thermal map at 1m off the floor

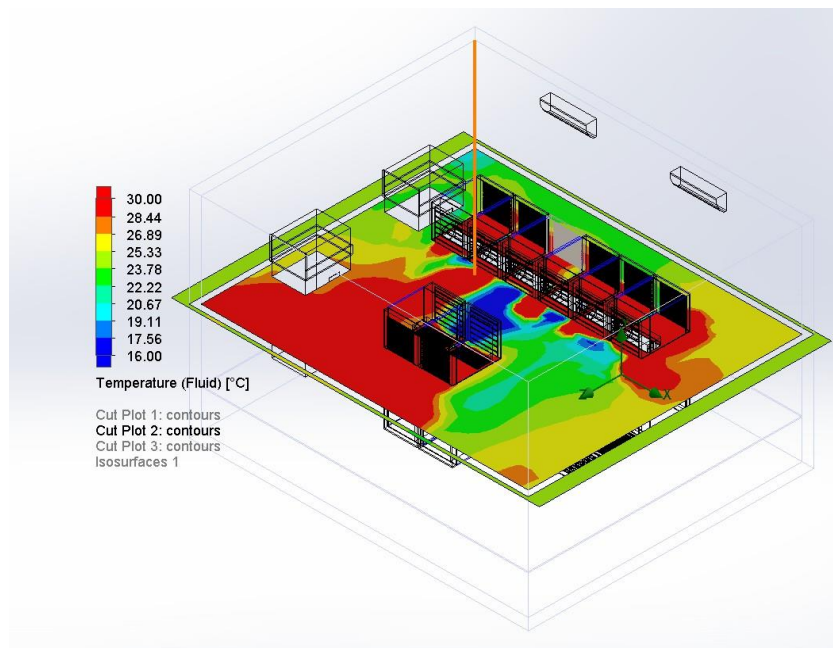


Figure 4.2: Thermal map at 2m off the floor

4.2.2 Thermal mapping recorded across the length and width of the data centre

The thermal mapping conducted at the midplane along the length and width of the

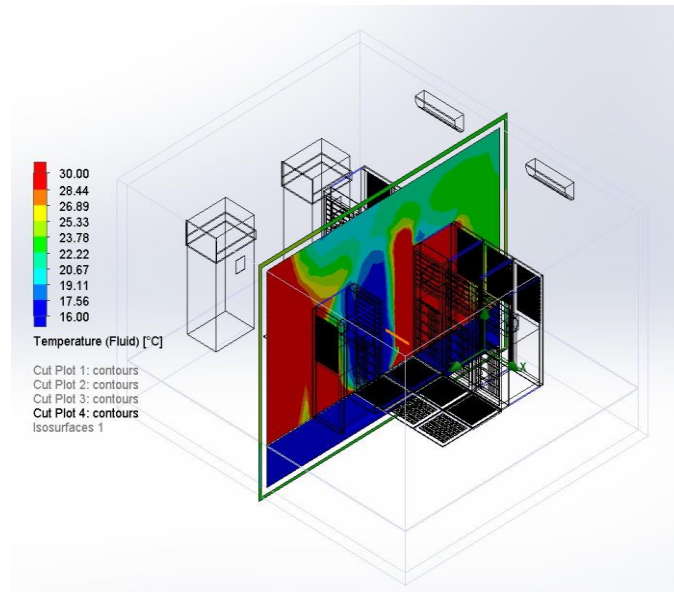


Figure 4. 3: Thermal map at the midplane along the width of DFCU data center

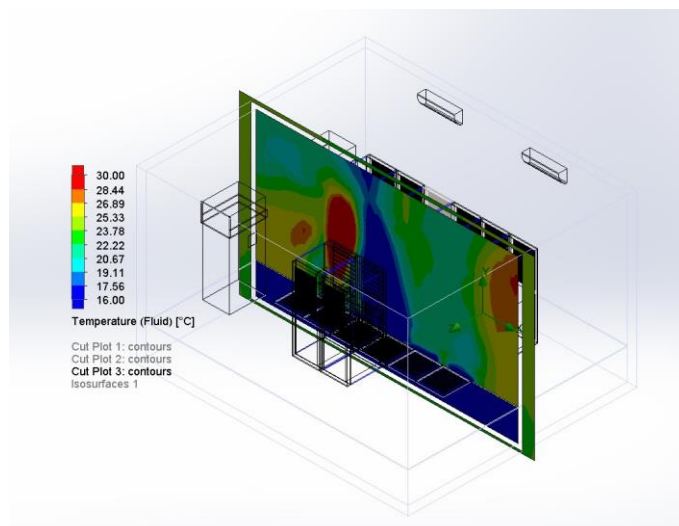


Figure 4. 4: Thermal map at the midplane along the length of DFCU data center.

DFCU data center, as shown in Figures 4.3 and 4.4, unveiled significant temperature gradients, particularly notable around the rack locations. These observations revealed distinct re-circulation patterns, especially evident in the surroundings of the racks, where hot air exiting into the hot aisle was observed to be forced back into the cold aisle from both the sides and the top of the rack. This phenomenon contributes to the mixing of

hot and cold air streams, potentially compromising temperature uniformity within the data center environment.

4.2.3 Thermal Map at Quarter and Three-quarter Plane Along the Width of Data Center

Further exploration of the thermal map at three-quarter plane positions along the width and length of the data center, as illustrated in Figure 4.5 and 4.6 respectively, revealed the presence of hot and cold air mixing, with a pronounced high-temperature zone along the width of the facility. Notably, maximum temperatures reaching approximately 30°C were observed at the three-quarter plane along the length, primarily attributed to flow re-circulation from the exhaust side of the cabinet. This localized high-temperature zone was identified at the rear of the second rack within the data center. In contrast, a distinct low-temperature zone was discerned along the width at the three-quarter plane, characterized by localized hot spots primarily around the rack area. Notably, an elevated temperature anomaly was also identified at the quarter-plane position along the width of the data center.

This deviation from expected temperature distributions can be attributed to the phenomenon of servers receiving a mixed air stream comprising room air and air discharged from server outlets, rather than the conditioned air supplied through the vent tiles in the raised floor system. Furthermore, the observed low temperatures in the cold aisle of Racks 01 through 06 were predominantly influenced by the presence of high wall units. However, it is noteworthy that these high wall units may have inadvertently contributed to exhaust air re-circulated from Racks 01 through 06, potentially affecting overall thermal dynamics within the data center environment.

4.2.4 Temperature Cloud at the Data Center

The temperature cloud profiles were shown in Figures 4.7 and 4.9.

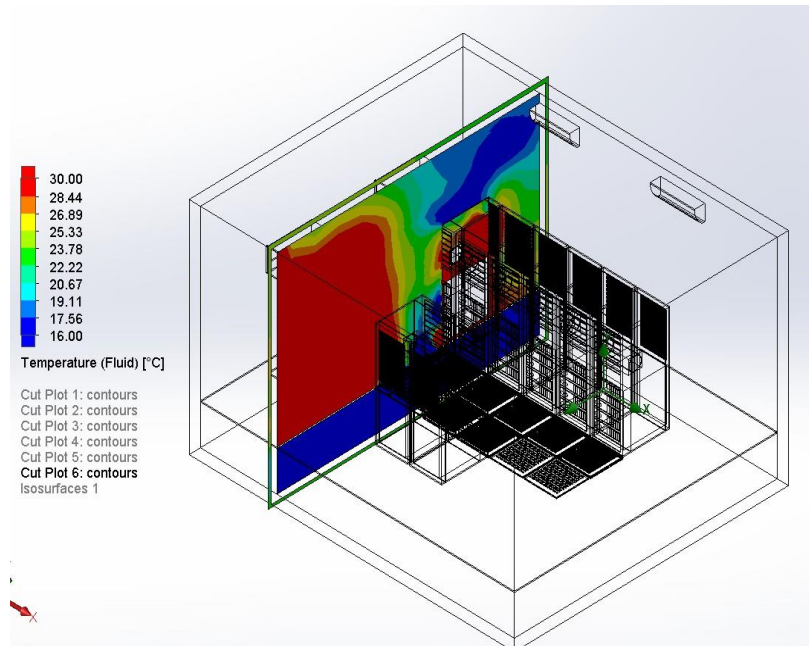


Figure 4. 5: Thermal map at quarter along the width data center.

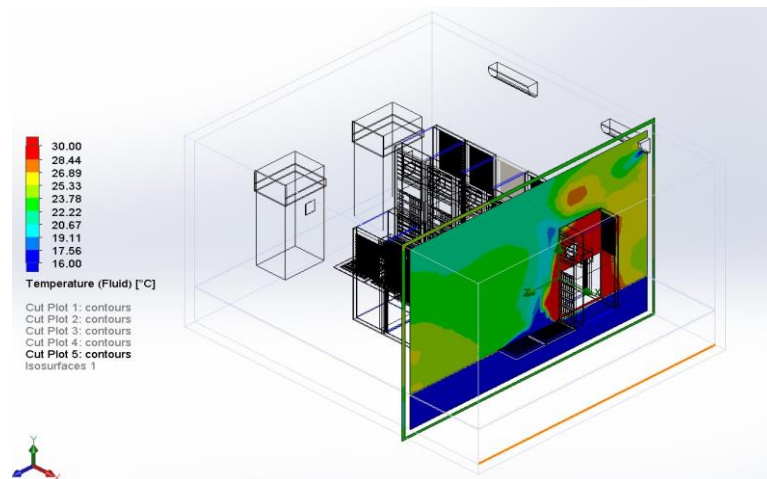


Figure 4. 6: Thermal map at three-quarter along the width data center.

From the analysis presented in Figures 4.7 and 4.9, it was evident that the highest concentration of temperature clouds was observed at the rear of the hot aisle within rack 07 and rack 08 of the data center. Notably, those regions already exhibited elevated temperatures, indicative of existing hot zones. Moreover, the temperature cloud pro-

files further indicated the presence of air recirculation phenomena occurring within the data center environment. Heat naturally flows from a region of higher temperature to one of lower temperature. This principle is a direct consequence of the second law of thermodynamics (Manjunath & Kaushik, 2014)

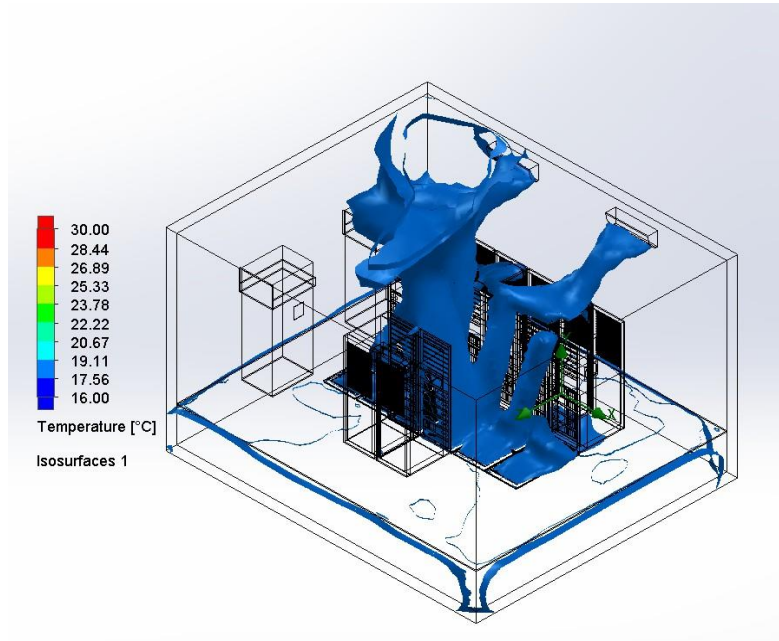


Figure 4.7: Low-temperature cloud at 19°C

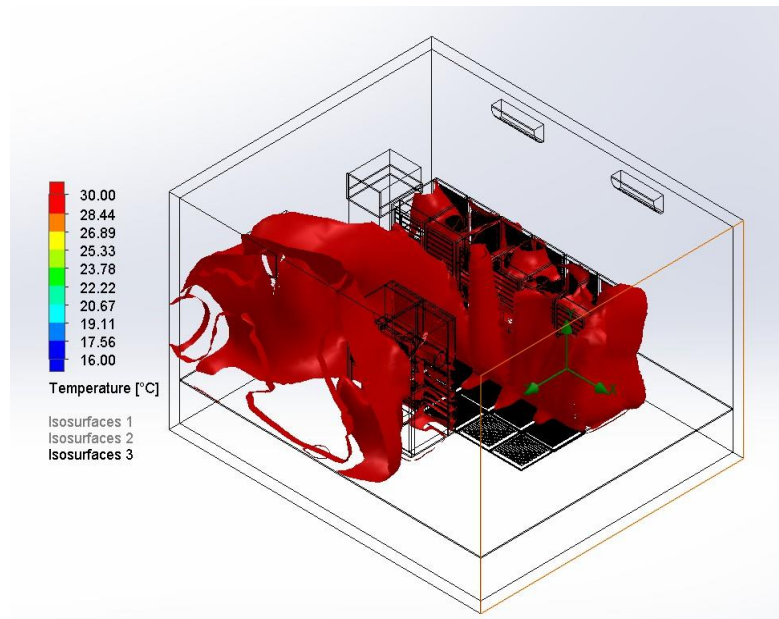


Figure 4. 8: High-temperature cloud at 30°C.

4.2.5 Hot-spots Zones in Data Center.

The study highlighted specific areas requiring airflow optimization as shown in Figure 4.9. These included:

- i) Zone along the hot aisles for racks 07 and 08.
- ii) Zone along the hot aisles for racks 01, 02, 03, 04, 05, and 06.

Insights from these areas inform the development of optimization strategies.

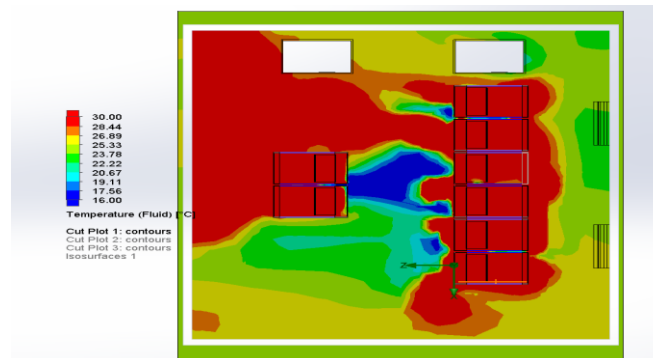


Figure 4.9: Illustrate hot spots and Poor Airflow Zones.

4.3 Proposed Optimization Layout

Based on the analysis conducted above, a proposed layout was developed aimed at optimizing airflow at the data center

Figures 4.10 and 4.11 shows the proposed layout used for the optimization of airflow at the DFCU data center. The figure shows additional two CRAC units, CRAC 03 and 04, the Return air duct, and the supply grill as a replacement for perforated tiles.

4.3.1 Cooling Load Summary

The table 4.1 shows data related to a data center's thermal management. Specifically, it includes information on the maximum heat load produced within the data center, the capacity of the CRAC units and High Wall Units (HWUs) installed to mitigate this heat, and the existing cooling capacity deficit at the DFCU data center

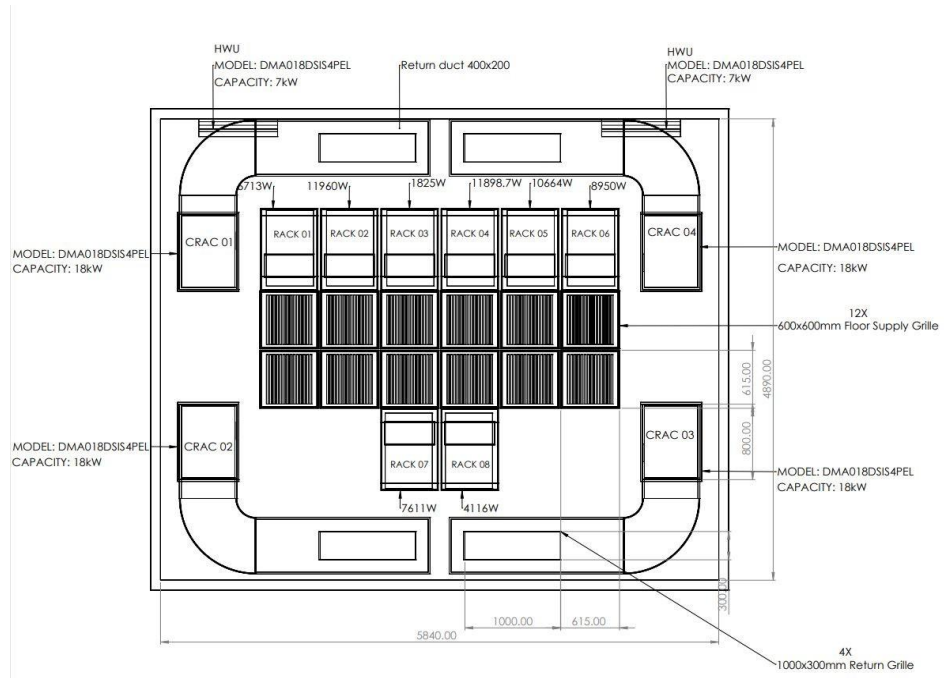


Figure 4. 10: Plan view of DFCU Data Center used for Optimization Simulation.

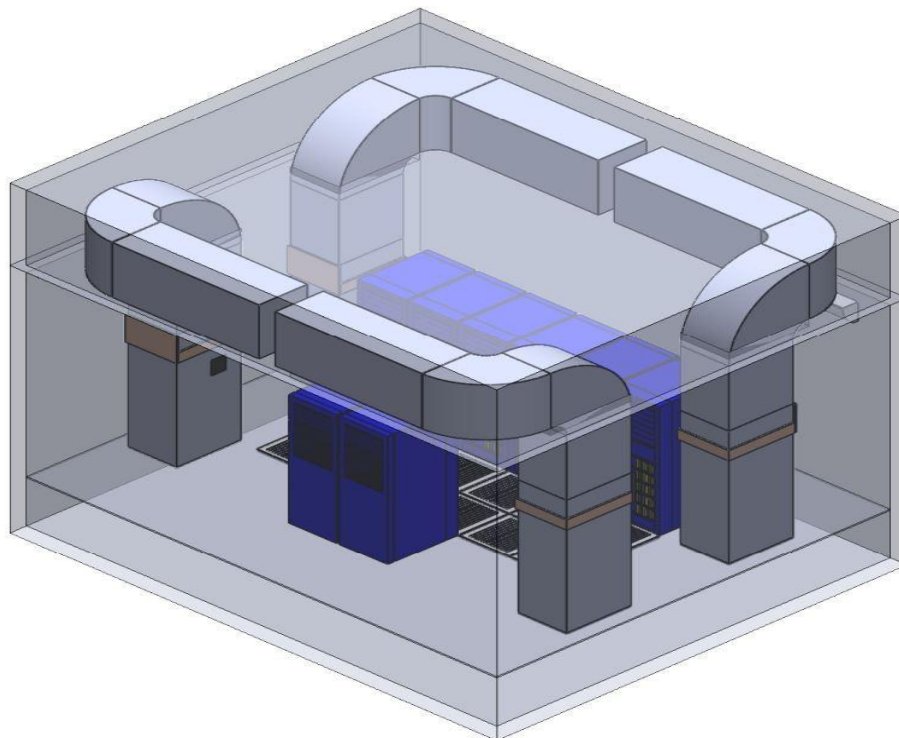


Figure 4. 11: 3D Geometry of DFCU Data Center Used for Optimization Simulation.

4.3.2 Optimization Result after Proposed Improvement

Taking into consideration the existing heat loads, there was a cooling deficit of 33 kW identified, as shown in the table below 4.1 To address this shortfall and achieve a balanced

Table 4. 1: Data Center AC Cooling Load Summary Sheet.

Maximum Heat load (W)	- 83,464.52
2no. Denco CRAC Units @18kW (W)	+ 36,000.00
2no. Samsung HWU @7kW (W)	+ 14,000.00
Current Cooling Deficit (W)	- 33,464.52

heat load within the data center, the implementation of additional cooling units was proposed. These units included supplementary CRAC units strategically placed. The enhanced 3D model utilized for optimization in this scenario is illustrated in Figure 4.11 below. The updated layout incorporates the integration of newly proposed CRAC units by incorporating these additional cooling units, the data center's cooling infrastructure produced an optimized result, as shown in Figures 4.12 through 4.23. Therefore, an additional cooling load of 36kW (selected from the catalog) was required to eliminate the current deficit and was sufficient to serve IT equipment but without considering future expansion. This load was divided into two units of 18kW each. Please note that ASHRAE recommends a cooling redundancy of 100% for data centers. That means the cooling infrastructure should be capable of handling double the expected cooling load, providing a level of redundancy to ensure uninterrupted operation, future expansion, and even in the event of equipment failure or maintenance activities. However, redundancy was considered for the study.

4.3.3 Thermal Mapping Recorded at Different Planes in Optimized Data Center Layout

The simulation study was conducted to analyze the optimization outcomes on thermal mapping above the raised floor, thermal mapping at the mid-plane along the length and width, and thermal mapping at a quarter and three-quarter points along the length of the data center together with the temperature cloud. The resultant output was visualized and presented in Figures 4.12 through 4.23, showcasing the geometric distribution of temperatures within the data center.

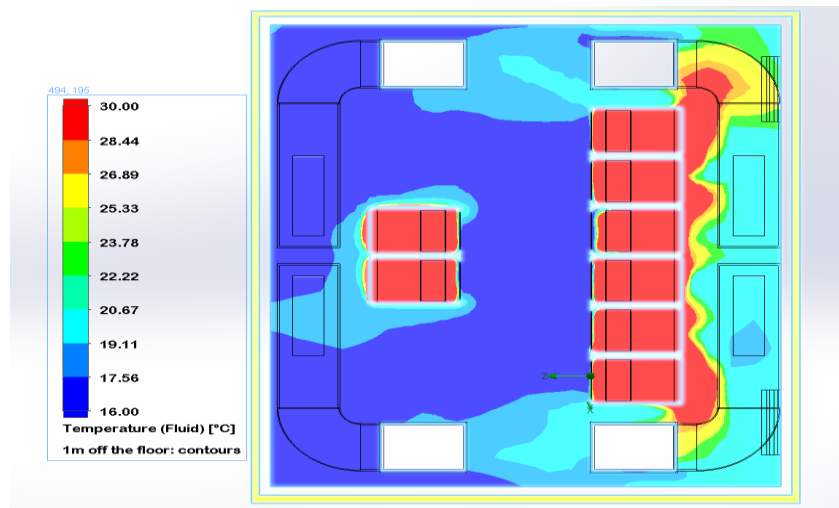


Figure 4.12: Optimized thermal map at 1m off the raised floor.

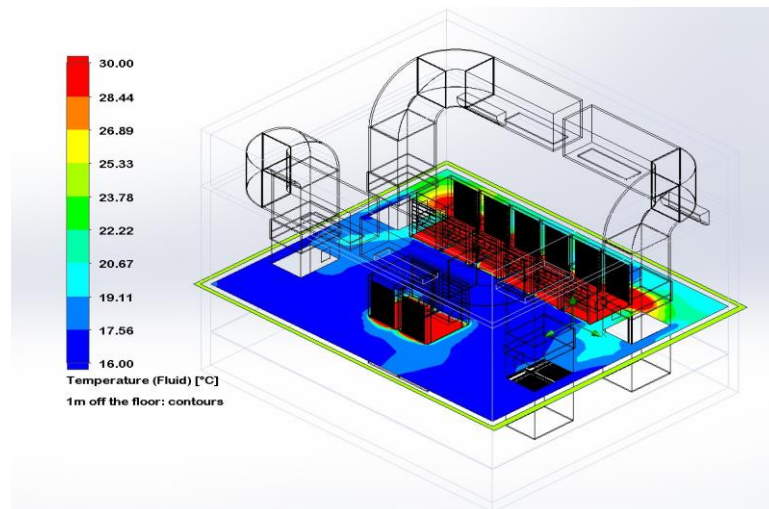


Figure 4.13: Top View of the optimized thermal map at 1m off the raised floor

4.3.4 Temperature Pattern at Different Heights Above the Raised Floor

The implementation of a return duct and an additional Computer Room Air Conditioning (CRAC) unit yielded a discernible decrease in temperature at the rear side of racks 07 and 08, effectively eliminating the potential for airflow recirculation observed in the initial configuration. Figure 4.12 through 4.15

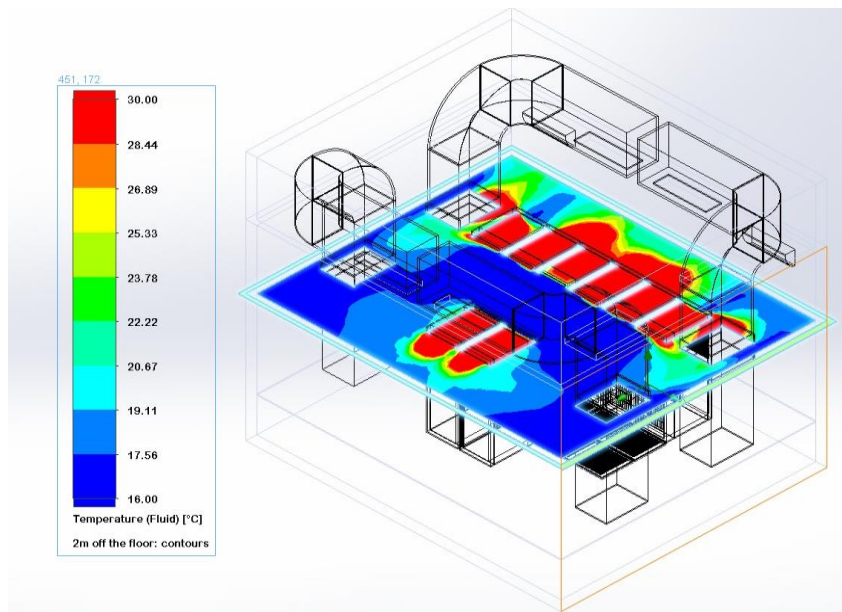


Figure 4. 14: Optimized thermal map at 2m off the raised floor.

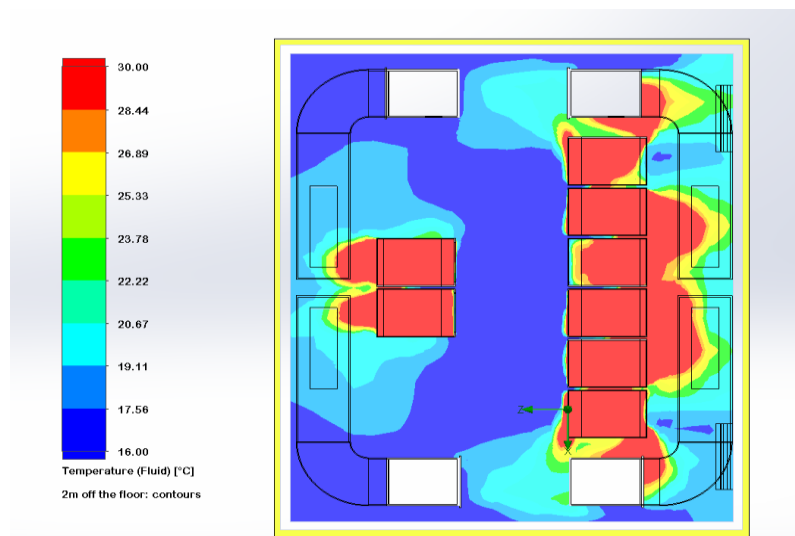


Figure 4.15: Top View of the optimized thermal map at 2m off the raised floor.

4.3.5 Thermal Mapping Recorded After Optimization Across the Length and Width of Data Center

The thermal mapping conducted at the midplane along the length and width of the DFCU data center, illustrated in Figures 4.16 through 4.19, uncovered a substantial reduction in temperature differentials, particularly pronounced in the vicinity of the rack

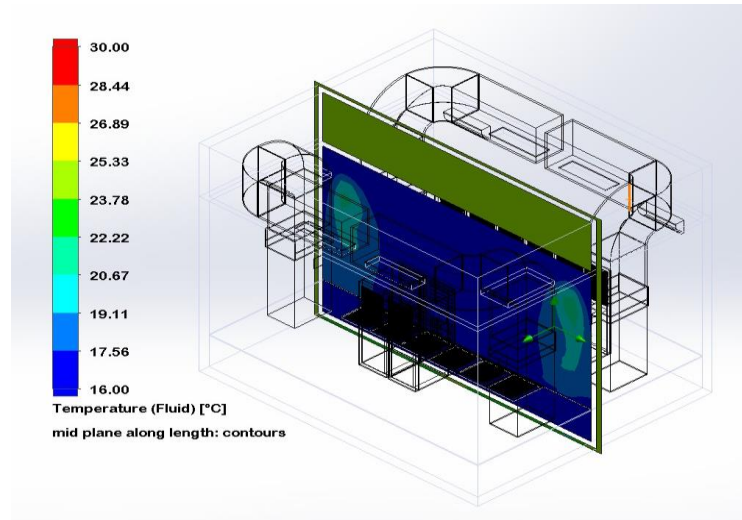


Figure 4. 16: Thermal map at the midplane along the length of the DFCU data centre.

These findings elucidated the elimination of recirculation patterns, notably observed in the vicinity of the racks as was the previous case.

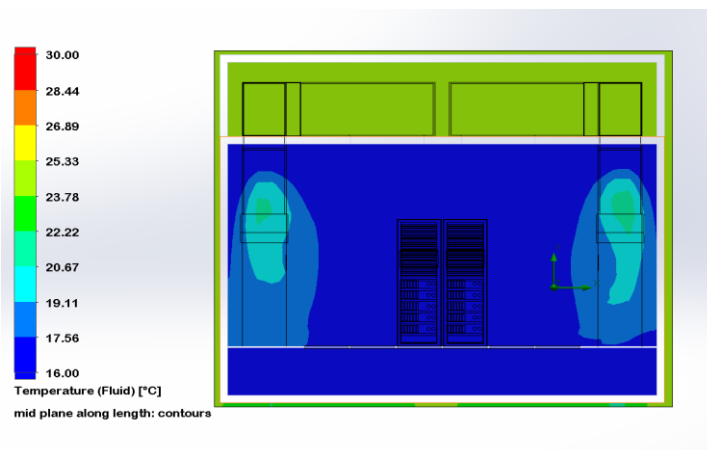


Figure 4. 17: Cross-sectional view of the optimized thermal map at the midplane along the length of DFCU Data Center.

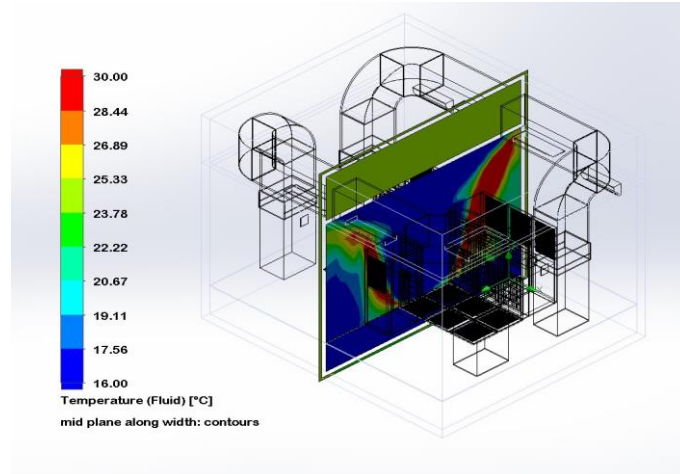


Figure 4. 18: Optimized thermal map at the midplane along the width of DFCU data center

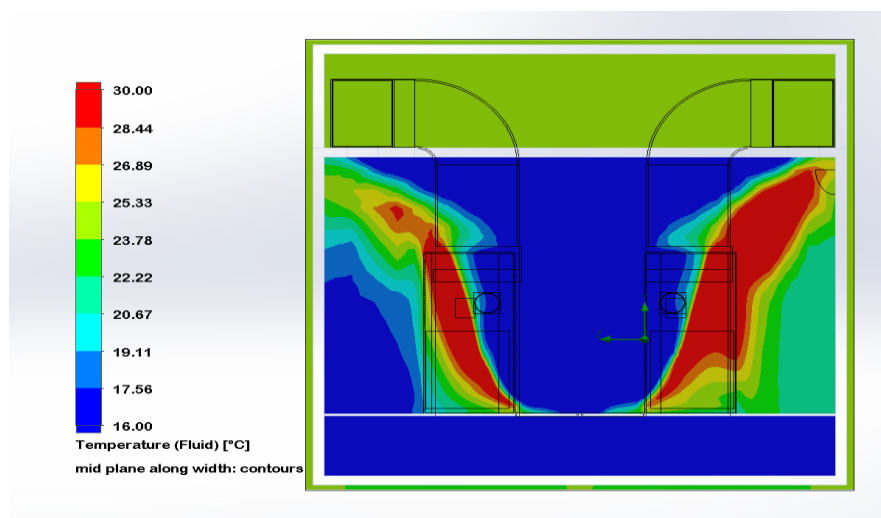


Figure 4.19: Cross Sectional View of the optimized thermal map at the midplane along the width of DFCU data center.

4.3.6 Optimized Thermal Map at Quarter and Three-quarter Plane Along the Width of Data Center After Optimization

Upon further examination of the thermal map at the quarter and three-quarter plane positions the length and width of the data Centre, shown in Figures 4.20 and 4.21, it was observed that there was no mixing of hot and cold air. Notably, a distinct high

temperature of 30°C was observed at the return grill installed on the duct, indicating a marked improvement in airflow patterns.

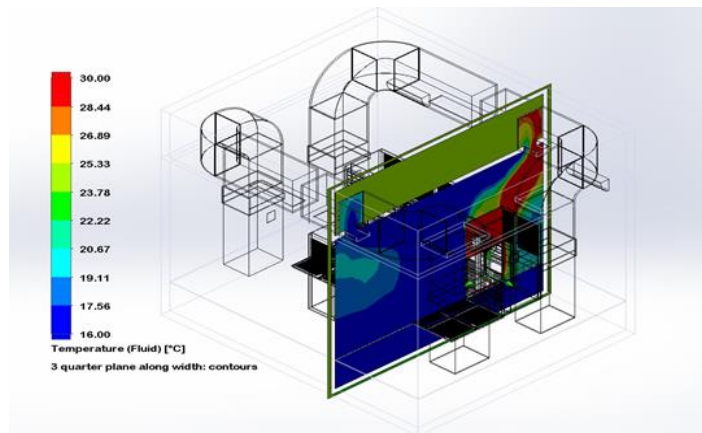


Figure 4. 20: Optimized thermal map at quarter along the width data center

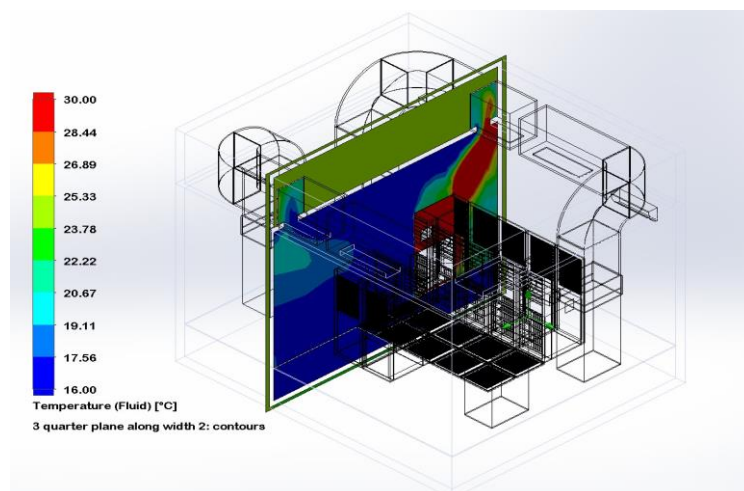


Figure 4. 21: thermal map at three-quarter along the width data center.

4.3.7 Temperature Cloud at the Data Center After Optimization

Figure 4.23 showed a notable decrease in the extent of the region characterized by a temperature of 30°C, primarily concentrated around the rack vicinity. The majority of the area within the data center exhibits an average temperature of approximately 19°C as illustrated in Figure 4.22, signifying substantial enhancement in thermal conditions.

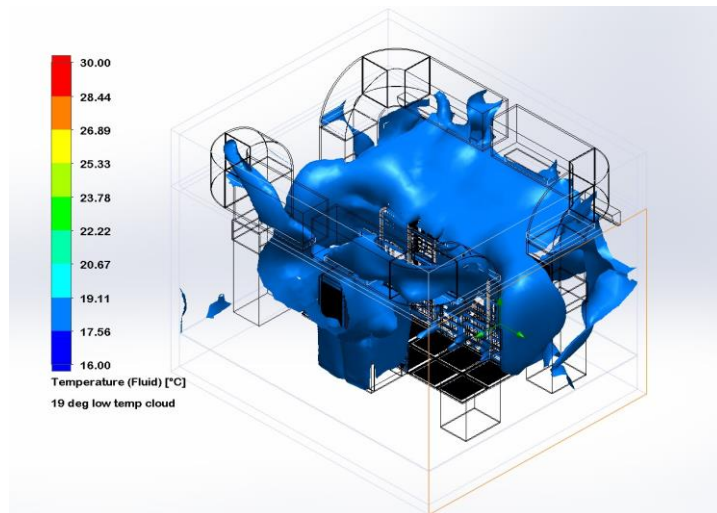


Figure 4.22: Optimized Low-temperature cloud at 19°C

The simulation results demonstrated a substantial enhancement in airflow within the data center due to the proposed layout.

Additionally, the strategic placement of the additional CRAC (Computer Room Air Conditioning) units has been validated as effective. Furthermore, the incorporation of a return duct has significantly reduced exhaust air recirculation, contributing to overall efficiency.

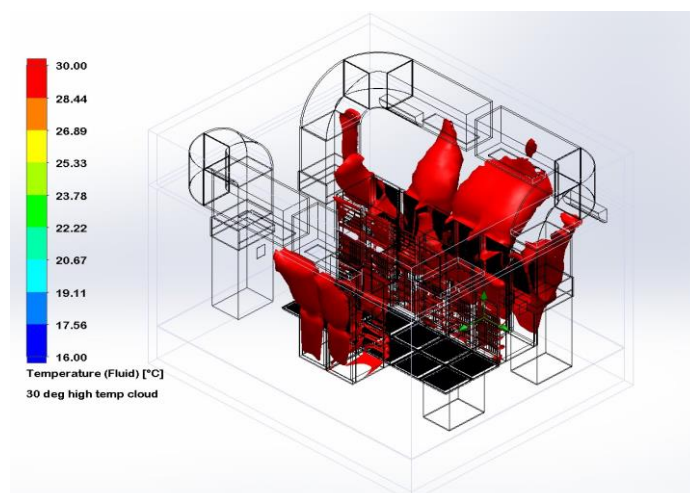


Figure 4. 23: Optimized High-temperature cloud 30°C

While rearranging server racks enhanced airflow and cooling efficiency by reducing hot spots and ensuring more uniform air distribution, it would not address the fundamental issue of a 36KW cooling load deficit. This deficit indicated that the current cooling units could not handle the total heat generated, leading to potential overheating, equipment failure, and reduced performance. Adding additional CRAC (Computer Room Air Conditioning) units was important to maintain optimal temperature, provide redundancy, improve energy efficiency, and ensure future scalability. Therefore, addressing the cooling load deficit by adding the required 36KW of CRAC units was essential for the reliable and efficient operation of the DFCU data center.

4.3.8 PUE of DFCU data center before and after Optimization

To calculate the Power Usage Effectiveness (PUE) of the DFCU data center before and after optimization, the following information was used;

1. Total Facility Power (TFP): This includes all the power consumed by the data center, including IT equipment, cooling systems, lighting, and other infrastructure.
2. IT Equipment Power (IEP): This is the power consumed solely by the IT equipment (servers, storage, network devices).

The formula for PUE is:

$$PUE = \frac{\text{Total Facility Power (TFP)}}{\text{IT Equipment Power (IEP)}}$$

Given the optimization scenario at the DFCU data center;

- The heat generation source (IT Equipment Power) remains constant at 84,000W.
- The CRAC cooling capacity increases from 50,000W to 86,000W.

4.3.9 Before Optimization

1. IT Equipment Power (IEP): 84,000W
2. Cooling Power: 50,000W

Assuming no other significant power consumers, the Total Facility Power (TFP) before optimization was:

$$TFP \text{ before} = IEP + \text{Cooling Power} = 84,000W + 50,000W = 134,000W.$$

So, the PUE before optimization was:

$$PUE \text{ before} = \frac{134,000W}{84,000W} \approx 1.60$$

4.3.10 After Optimization

1. IT Equipment Power (IEP): 84,000W
2. Cooling Power: 86,000W

The Total Facility Power (TFP) after optimization was:

$$TFP \text{ after} = IEP + \text{Cooling Power} = 84,000W + 86,000W = 170,000W.$$

So, the PUE after optimization is:

$$PUE \text{ after} = \frac{170,000W}{84,000W} \approx 2.02$$

Summary;

- PUE before optimization: 1.60
- PUE after optimization: 2.02

4.3.11 Explanation

Increasing the cooling capacity has increased the PUE, indicating a decrease in overall efficiency. This suggests that while the cooling capacity has increased, it may not be optimized for energy efficiency.

Balancing the heat generation with the cooling capacity was important for maintaining the reliability and performance of the data center. However, the increase in PUE due to adding more CRAC units was a concern. The following justifications and considerations were made for this approach:

4.3.12 Justifications for Adding More CRAC Units

1. Ensuring Thermal Stability.

- **Preventing Overheating:** The primary goal was to prevent overheating of IT equipment, which could lead to hardware failures and downtime. Ensuring adequate cooling capacity was essential for maintaining thermal stability.
- **Maintaining Optimal Performance:** Proper cooling ensured that servers and other IT equipment operated within their optimal temperature range, which enhanced performance and longevity.

2. Redundancy and Reliability

- **Redundancy:** Adding more CRAC units provided redundancy, ensuring that if one unit failed, others could take over, maintaining the cooling requirements.
- **Reliability:** Increased cooling capacity improved the overall reliability of the data center by reducing the risk of thermal-related issues.

3. Future-Proofing

- Scalability: As data centers grew and IT loads increased, additional cooling capacity accommodated future expansion without needing immediate upgrades.
- Flexibility: More CRAC units provided flexibility in managing varying loads and could be adjusted based on real-time cooling demands.

4.3.13 Addressing the Increase in PUE

- While adding more CRAC units led to an increase in PUE, several strategies were suggested to mitigate this impact and improve overall energy efficiency. These strategies included;
- Variable Speed Drives (VSDs): The CRAC units with VSDs compressors should be selected to adjust the cooling output based on real-time demand, reducing energy consumption during lower loads.
- Efficient Scheduling: Intelligent scheduling should be enforced such that the CRAC units run only when needed, avoiding unnecessary energy use.
- Regular Maintenance and Upgrades: The CRAC units should be regularly maintained and cleaned to operate efficiently.
- Upgrade to Efficient Units: More energy-efficient CRAC units with higher Coefficient of Performance (COP) ratings were considered for upgrades.

4.3.14 Rack Cooling Index (RCI) of DFCU data center Before and After Optimization

- The RCI measures how well the racks' intake temperatures are maintained within the recommended range set by ASHRAE.

The formula for RCI is given by:

Calculate the sum of deviations:

$$RCI = \frac{100\% \times (T_{max} - T_{min}) - \sum_{i=1}^n (\max(T_i - T_{max}, 0) + \max(T_{min} - T_i, 0))}{T_{max} - T_{min}}$$

Where:

- T_{max} is the maximum recommended temperature ($27^{\circ}C$),
- T_{min} is the minimum recommended temperature ($18^{\circ}C$),
- T_i are the intake temperatures of the racks.

4.3.15 Rack Cooling Index (RCI) of DFCU Data Center Before Optimization

Given:

- $T_{max} = 27^{\circ}C$
- $T_{min} = 18^{\circ}C$
- $T_1 = 28^{\circ}C, T_2 = 30^{\circ}C, T_3 = 20^{\circ}C, T_4 = 21^{\circ}C, T_5 = 22^{\circ}C, T_6 = 28^{\circ}C, T_7 = 19^{\circ}C, T_8 = 19^{\circ}C$

Calculate the sum of deviations:

$$\sum_{T=1}^8 (\max(T_i - 27, 0) + \max(18 - T_i, 0))$$

For each T_i :

$$T1 = 30 : (\max(30 - 27, 0) + \max(18 - 30, 0)) = (3 + 0)$$

$$T2 = 30 : (\max(30 - 27, 0) + \max(18 - 30, 0)) = (3 + 0)$$

$$T3 = 23 : (\max(23 - 27, 0) + \max(18 - 23, 0)) = (0 + 0)$$

$$T4 = 21 : (\max(21 - 27, 0) + \max(18 - 21, 0)) = (0 + 0)$$

$$T5 = 29 : (\max(29 - 27, 0) + \max(18 - 29, 0)) = (2 + 0)$$

$$T6 = 29 : (\max(29 - 27, 0) + \max(18 - 29, 0)) = (2 + 0)$$

$$T7 = 19 : (\max(19 - 27, 0) + \max(18 - 19, 0)) = (0 + 0)$$

$$T8 = 19 : (\max(19 - 27, 0) + \max(18 - 19, 0)) = (0 + 0)$$

Sum of deviations: $3 + 3 + 0 + 0 + 2 + 2 + 0 + 0 = 10$

Substitute the values into the RCI formula:

$$RCI = \frac{100\% \times (27 - 18) - 10}{27 - 18}$$

$$RCI = \frac{100\% \times 9 - 10}{9} = \frac{900 - 10}{9} = \frac{890}{9} \approx 98.9\%$$

The Rack Cooling Index (RCI) is approximately 98.9%, indicating that most intake temperatures were within the recommended range, with a few deviations.

4.3.16 Rack Cooling Index (RCI) of DFCU Data Center After Optimization

Since all T_i values are within the range of $18^\circ\text{C} \leq T_i \leq 27^\circ\text{C}$, the deviations are zero:

$$\sum_{i=1}^n (\max(T_i - 27, 0) + \max(18 - T_i, 0))$$

Substitute the values into the RCI formula:

$$RCI = \frac{100\% \times (27 - 18) - 0}{27 - 18}$$

Simplify the expression:

$$RCI = \frac{100\% \times 9 - 0}{9} = \frac{900 - 0}{9} = \frac{900}{9} \approx 100\%$$

The Rack Cooling Index (RCI) after optimization, 100%, indicating optimal cooling performance

CHAPTER FIVE: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary of Findings

1. **CRAC Capacity Check.** The data center's Cooling Resource Adequacy Capacity (CRAC) was assessed. The combined existing cooling demand from the data center is quantified at 50 kW, while the cumulative heat generation from IT equipment, lighting, and personnel stands at 84 kW. Consequently, the current cooling capacity is insufficient to effectively manage the heat generated by the data center, particularly when it operates near peak capacity. Additionally, the cooling system lacks adequate redundant capacity, making maintenance of any single unit within the system potentially disruptive to data center operations.

2. **CRAC Unit Check.** In the examined period, no conflict in demand allocation was observed between the two Computer Room Air Conditioning (CRAC) units, both of which were functioning under identical operational modes. However, the potential for demand conflict exists between the CRAC units and the High Wall Units. While the CRAC units offer four operational modes (cooling, heating, humidification, and dehumidification), the High Wall Units are limited to only two modes (cooling and dehumidification). Consequently, synchronization of operation between the CRAC and High Wall Units is unfeasible due to their disparate operational capabilities. Notably, the CRAC units operated within standard parameters during the data collection.

3. **The CRAC Unit and Floor Grill Placement.** The positioning of floor grills and Computer Room Air Conditioning (CRAC) units is determined to be optimal, ensuring efficient airflow and cooling distribution. However, placing High Wall

Units in the hot aisle is deemed suboptimal, potentially compromising cooling effectiveness. During the data collection, the CRAC units were found to be operating within normal parameter

The average supply temperature at the grills was recorded at 19⁰C, while the average room temperature, estimated from 30 measurements taken across the Data Center, was approximately 23⁰C. The CRAC units were set to maintain a temperature of 18⁰C with a relative humidity target of 50%.

4. Check aisle and Rack temperature. According to ASHRAE guidelines, the recommended temperature range for reliable operation of most classes of IT equipment in a data center falls between 18⁰C and 27⁰C. Although the measured temperatures fall within this range in some zones within the data center, significant fluctuations exist between the lowest and highest recorded temperatures.
5. Return air was not ducted through ceiling grills back to the CRAC units and there was no physical barrier between the hot and cold aisle. This prevented optimal flow of cold air through the equipment creating hot spots in the hot aisle. Measurements for temperature were taken at 30 points around the IT racks and CRAC units. The maximum temperature measured was 30⁰C behind Sun Oracle SPARC T7-2 on Rack
7. The minimum temperature measured was 16⁰C at the floor grills. The average temperature of the return air to the Computer Room Air Conditioning (CRAC) units was measured at 29⁰C, indicating sub-optimal airflow and the possibility of hazardous hot spots within the data center.

6. Redundancy. The available total cooling load is 50kW supplied by the CRAC and High Wall Units. The total heat load is 84kW from IT equipment, lights, UPS, power distribution equipment, and personnel. There is no redundant cooling load.

7. Improved Airflow Dynamics in the Data Center. The incorporation of two additional 18 kW Computer Room Air Conditioning (CRAC) units, along with the implementation of a return duct, has resulted in a more uniform temperature distribution within the data center. This enhancement has notably reduced the occurrence of hot-spot zones, thus improving overall airflow dynamics.

While adding more CRAC units initially increased the PUE, the primary goal was to ensure the data center's thermal stability and reliability. The impact on PUE was mitigated by implementing optimization strategies and focusing on energy efficiency, achieving a balanced, efficient cooling system.

8. The optimization of the data center cooling system has yielded a Rack Cooling Index (RCI) of 100%, signifying optimal cooling performance.

5.1 Conclusions

The comprehensive findings of this research reveal that the current cooling capacity is inadequate to satisfy both present and future demands. The research focused on enhancing and devising an airflow management system for the data center, pinpointing potential high-temperature zones within the computer racks. Notably, elevated temperature zones were identified along the length and width mid-plane of the data center, with a maximum temperature of approximately 30°C observed at the three-

quarter plane along the length, situated behind the second rack, attributed to recirculating flow from the exhaust side of the computer rack.

The average supply temperature was determined to be 23⁰C, while return temperatures of the CRAC units ranged between 25⁰C and 29⁰C, with maximum inlet temperatures recorded at 25⁰C and exit temperatures to the rack reaching 30⁰C. These findings offer critical insights into the operational performance of computer room air conditioning units and provide detailed temperature analyses, along with 3D thermal mapping highlighting areas of thermal concern.

This research presents a promising avenue for addressing thermal management challenges within the DFCU data center, offering a detailed 3D analysis of cold air distribution and proposing strategies for improved thermal performance. The results hold significant potential for informing future data center designs in Uganda, facilitating the development of tailored cooling strategies to optimize thermal efficiency. Moreover, the study's methodology can be extended to evaluate the impact of various cooling resources such as equipment layout, airflow rates, floor tiles, heat load distribution, and supplementary cooling strategies, thereby providing valuable insights for optimizing data center cooling operations. Additionally, the study proposes temperature estimates based on specific rack loading conditions, further enhancing its applicability in real-world data center environments.

5.2 Recommendations

The overall finding from the study is that the existing cooling load is insufficient to meet current and future demand. Arising out of this study, the researcher recommends the following actions for consideration;

1. To provide for sufficient cooling, install an additional 36kW of cooling load using 2no. 18kW DENCO CRAC units.
2. To prevent demand fighting, operate High Wall Units only in cooling mode. Dehumidification and humidification are to be performed by the CRAC units.
3. To improve airflow distribution and eliminate hotspots, existing and additional units should have returned air ducted from the hot aisles as shown in Figure 4.11
4. Provide blanking panels in rack spaces where IT equipment is not installed.
5. Additional supply grills should be provided.
6. To address the increase in PUE due to adding more CRAC units at the data center, several strategies were suggested to mitigate this impact and improve overall energy efficiency. These strategies included;
 - Variable Speed Drives (VSDs): Implement VSDs to adjust the cooling output based on real-time demand, reducing energy consumption during lower loads.
 - Efficient Scheduling: Utilize intelligent scheduling to operate CRAC units only when needed, avoiding unnecessary energy use.
 - Regular Maintenance: Routine Maintenance: Regularly maintain and clean CRAC units to ensure they operate efficiently.
 - Upgrade to Efficient Units: Consider upgrading to more energy-efficient CRAC units with higher Coefficient of Performance (COP) ratings.
 - Energy Monitoring and Management: Implement real-time monitoring systems to track energy usage and identify inefficiencies.

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APPENDICES

Appendix A: DFCU Data Center It Equipment Log

Annex One: dfcu Data Center ITE Log

Equipment	Max. Power Consumption/ Thermal Out Put
Rack 1	
MikroTik X2 RouterBoard 1100 AH	25.00
Cisco 1900 series	80.00
Huawei smart ax MA5612	78.00
Cisco ASA 5545-X	125.00
Cisco ASA 5545-X	125.00
Juniper Networks SSG 5	312.00
Juniper Networks SSG 5	312.00
Cisco 2500 series model 2504	22.00
Cisco 800 series	80.00
Cisco Catalyst 2960-s series	740.00
HP ProLiant DL360 G7	750.00
AVAYA G450	522.00
Cisco Catalyst 4503-E	4,200.00
Core i3 DELL CPU	240.00
R1 Total	7,611.00
Rack 2	
Cisco Catalyst 2960-s series	740.00
Cisco Catalyst 2960-s series	740.00
Cisco Catalyst 2960-s series	740.00
ETX-203AX	23.00
Cisco 800 series	80.00
Cisco 2911	750.00

Figure A.1: Rack 1 and 2

Equipment	Max. Power Consumption/ Thermal Out Put
Alcatel Lucent 7210 SAS-D ETR Service access Switch 6-SFP/4-TX	200.00
AVAYA IP500 V2 Control unit	115.00
AVAYA G450	522.00
Microtik RouterBoard RB260GS	6.00
Alcatel-Lucent 7210 SAS-D ETR	200.00
R2 Total	4,116.00
Rack 3	
NetApp DS2246	750.00
NetApp DS2246	750.00
DS14 Mk4	750.00
DS14 Mk4	750.00
DS14 Mk4	750.00
NetApp FAS3140	750.00
DS14 Mk4	750.00
DS14 Mk2	750.00
DS14 Mk2	750.00
Cisco Catalyst 3850 24 (s/no. C3850-NM-4-1G)	1,100.00
Cisco Catalyst 3850 24	1,100.00
R3 Total	8,950.00
Rack 4	
Brocade 300 Fibre Channel Switch	81.00
Brocade 300 Fibre Channel Switch	81.00
HP Proliant DL360 G7 (s/no. CZJ1200LF6)	750.00
HP Proliant DL360 G7	

Figure A.2: Rack 3 and 4

Equipment	Max. Power Consumption/ Thermal Out Put
	750.00
HP Proliant DL360 G7	750.00
Sun microsystems StorageTek SL48	312.00
Sun Blade 6000	5,740.00
HP Blade System c7000 (s/no. CZ3140W8EL)	2,400.00
R4 Total	10,864.00
Rack 5	
DELL Power Connect 6224	69.90
BOSCH NVR DIP-7284-8HD	332.20
BOSCH NVR DIP-7284-8HD	332.20
BOSCH NVR DIP-7284-8HD	332.20
BOSCH NVR DIP-7284-8HD	332.20
HP Proliant DL360 G5	750.00
HP Proliant DL360 G7	750.00
HP Proliant DL360 G7	750.00
HP Proliant DL360 G7	750.00
HP Proliant DL360 G7	750.00
HP Proliant DL360 G7	750.00
HP Proliant DL360 G5	750.00
HP Proliant DL380P Gen8	750.00
HP Proliant DL380 G5	750.00
HP Proliant DL380 G7	750.00
HP Proliant DL380 G7	750.00
HP Proliant DL380 G7	750.00
HP Proliant DL380 G7	750.00

Figure A.3: Rack 6

Equipment	Max. Power Consumption/ Thermal Out Put
	750.00
HP Proliant DL380 G5	750.00
HP Proliant DL380 G5	750.00
R5 Total	11,898.70
Rack 6	
7042-CR5 IBM HMC	675.00
IBM Power 520 8203-E4A server	950.00
Thales payshield HSM9-12S	100.00
Thales payshield HSM9-12S	100.00
R6 Total	1,825.00
Rack 7	
Cisco DS-C48S-300AC	300.00
Cisco DS-C48S-300AC	300.00
Cisco DS-C48S-300AC	300.00
Cisco DS-C48S-300AC	300.00
Cisco ASA 5545-X	125.00
Cisco ASA 5545-X	125.00
BIG-IP i4000 series	130.00
HP Enterprise Storage Array NMBLA-0002-1200	550.00
Radware Alteon 5208	140.00
Radware Alteon 5208	140.00
Sun Oracle SPARC T7-2	2,475.00
Sun Oracle SPARC T7-2	2,475.00
Dell EMC PowerEdge R640	1,600.00

Figure A.4: Rack 6 and 7

Equipment	Max. Power Consumption/ Thermal Out Put
C3K Nimble Storage	500.00
Cisco UCS 5108	2,500.00
R7 Total	11,960.00
Rack 8	
Cisco Catalyst 3750 Series 3750G-48PS	202.00
Juniper Networks SRX345	123.00
Juniper Networks SRX345	123.00
DELL PowerEdge R610	717.00
Cisco Catalyst 3750 Series 3750G-48PS	202.00
Juniper Networks SRX345	123.00
Juniper Networks SRX345	123.00
HP Proliant DL325 Gen10 Plus	750.00
HP Proliant DL380 Gen10	750.00
HP Enterprise Storage Array Model: NMBLA-002-1200	550.00
Cisco UCS 5108	2,500.00
HP Enterprise Storage	550.00
R8 Total	6,713.00
Miscellaneous	
DELL Optiplex 755	470.00
DELL PowerEdge T110 II	305.00
Sunfire V890 (3no., 3200W@)	9,600.00
Lights (21.53 x floor area (sq m))	658.82
UPS	5,590.00
Power Distribution	

Figure A.5: Rack 8

Equipment	Max. Power Consumption/ Thermal Out Put
	2,043.00
Lighting	660.00
Personnel (2no., 100W@)	200.00
Miscellaneous Heat load (W)	19,526.82
Total Heat load (W)	83,464.52

Figure A.6: Total Rack load

Appendix B: Introductory letters

Appendix C: Plagiarism Test Results