STM JOURNALS

Trends in
Machine Design

https://journals.stmjournals.com/tmd/

ISSN: 2455-3352
Volume 11, Issue 3, 2024
September–December
DOI (Journal): 10.37591/TMD

Research TMD

Enhancing Energy Efficiency in HVAC Systems: A Comprehensive Study of EC+ Fans, VFDs, and AI Integration

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Abstract

This research paper explores the integration of EC+ fans with Variable Frequency Drives (VFDs) and Permanent Magnet (PM) motors to enhance energy efficiency and operational performance in heating, ventilation, and air conditioning (HVAC) systems. An extensive energy audit was conducted at the BidP plant in Bangalore, focusing on air handling units (AHUs) in Hangar 101. The audit revealed substantial variations in fan efficiency, secondary fan performance, power consumption, and airflow rates, particularly between the North and South sides of the hangar. To optimize the HVAC design, key calculations were performed, including heating load and cooling load assessments, airflow (CFM) evaluations, and pressure drop analyses through ductwork. These calculations utilized established formulas and methodologies, leading to a better understanding of the facility's thermal dynamics and the heat transfer requirements of clean rooms. The findings indicated that axial flow fans significantly outperform centrifugal fans in efficiency and reliability, achieving a total efficiency of approximately 85% while providing smooth airflow with minimal pressure loss. Moreover, the proposed solution architecture involves implementing an AI model for dynamic control of AHUs based on real-time sensor data, allowing for adaptive modulation of airflow and energy consumption. This paper highlights the critical role of advanced technologies in achieving sustainable HVAC solutions and reducing carbon emissions. The insights gained from this research will guide future implementations of energy-efficient systems, promoting best practices in facility management while contributing to the broader goals of environmental sustainability and energy conservation in industrial applications.

Keywords: Energy efficiency, EC+ Fans, HVAC systems, clean room technology, air handling units (AHUs)

INTRODUCTION

The HVAC (Heating, Ventilation, and Air Conditioning) industry is undergoing a transformation driven by the urgent need for energy-efficient solutions amidst rising energy costs and environmental concerns. The integration of advanced technologies, such as Variable Frequency Drives (VFDs) and Permanent Magnet (PM) motors, has become critical for optimizing the performance of air handling units (AHUs). This paper investigates the electrical configurations necessary for the effective integration of EC+ fans with VFDs and PM motors, focusing on the electrical connections, control circuits, and associated components. In HVAC systems, accurate calculations of heating and cooling loads, airflow (CFM), and pressure drops are essential for designing effective ductwork. This study also includes an energy audit conducted at the BidP plant

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Received Date: October 25, 2024
Accepted Date: October 29, 2024
Published Date: December 31, 2024

Citation: Dhanush M., Shivashankar Hiremath, Subramanya R Prabhu B. Enhancing Energy Efficiency in HVAC Systems: A Comprehensive Study of EC+ Fans, VFDs, and AI Integration. Trends in Machine Design. 2024; 11(3): 44–54p.

in Bangalore, which revealed notable variations in AHU efficiency and energy consumption. By comparing the performance of axial flow fans against traditional centrifugal fans, this research seeks to identify optimal solutions for enhancing HVAC system efficiency. Furthermore, the development of an AI-based solution architecture aims to demonstrate the potential for real-time monitoring and adaptive control, ultimately promoting sustainability in industrial HVAC applications [1].

METHODS

Electrical Connection of EC+ Fan

The electrical connection of Ec+ fans with a Variable Frequency Drive (VFD), Permanent Magnet (PM) motor, and main Miniature Circuit Breaker (MCB) involves several steps. Firstly, the PM motor is wired to the VFD by connecting its U, V, and W wires to the respective output terminals of the VFD. Secondly, the fans are connected to the PM motor, with their positive wires linked to one of the PM motor's terminals and the negative wire connected to the ground terminal. The VFD, on the other hand, is connected to the main MCB through its three input wires (L1, L2, and L3) which correspond to the phases of the MCB. Additionally, the ground wire of the VFD is connected to the ground wire of the main MCB. Lastly, the control circuit of the VFD, comprising start, stop, and speed control wires, is linked to push button switches and a potentiometer, enabling control over the PM motor's speed. This comprehensive electrical connection facilitates the integration of Ec+ fans with the VFD, PM motor, and main MCB, enabling efficient and adjustable operation of the system [2-4].

Formulas are used in ductwork calculation

a. Heating Load Formula:
The formula for calculating the heating load is given by:

$$HL=(Q \times \Delta T \times H)/(\eta \times Qa)\ldots \qquad (1)$$

Where:
HL = Heating Load
Q = Heat transfer rate
ΔT = Design Temperature Difference
H = Hours of Heating
η = Heating System Efficiency
Qa = Air Flow Rate

The above equation 4.1 is used to calculate the amount of heat that is generated by the clean rooms in the facility. This heat load must be accounted for when designing the HVAC system for the facility, to ensure that the clean rooms remain at the desired temperature [5].

b. Cooling Load

$$Q = \frac{TL \times CE}{AF}\ldots \qquad (2)$$

where:
Q = Cooling Load (BTU/hr.)
TL = Thermal Load (BTU/hr.)
CE = Cooling System Efficiency (%)
AF = Air Flow Rate (cfm)

Equation 4.2 is used to calculate the amount of heat that needs to be removed from the clean rooms in the facility to maintain the desired temperature and humidity.

c. The CFM (Cubic Feet per Minute) of a building is the volume of air moved or circulated within the building in one minute, essential for HVAC system design to maintain proper ventilation and indoor comfort. The below equation 4.3 is used to calculate CFM.

$$CFM = \frac{\text{Volume of space} \times ACH}{60}\ldots \qquad (3)$$

d. Pressure drop calculation

The calculation of pressure drop in ductwork involves several factors, including the size and shape of the ducts, the air flow rate, and the type of fittings used. Here are the basic steps for calculating pressure drop in ductwork:

Determine the air flow rate: The first step is to determine the air flow rate through the duct. This can be calculated using the formula:

$$\text{Pressure drop} = \frac{(\mathbf{FF \times L \times V * 2})}{(\mathbf{2 \times d})} \ldots \tag{4}$$

Where:
V= velocity
FF= Friction factor
d= diameter.

Length = the length of the duct section (in feet).

The formula to find the pressure drop in ductwork due to frictional losses in straight sections can be calculated using the Darcy-Weisbach equation:

$$\Delta P = f \times \frac{L}{D} \times \frac{\rho}{2} \times V * 2 \ldots \tag{5}$$

Where:
ΔP = pressure drop (inches of water)
f = friction factor
L = length of the duct (feet)
D = hydraulic diameter of the duct (feet)
ρ = density of the air (pounds per cubic feet)
V = velocity of the air (feet per minute)

Using the given values, we can calculate the pressure drop due to friction in the duct:

- Hydraulic diameter = 9.9 inches
- Air velocity = 351.1 feet per minute
- Reynolds number = 29,905
- Friction factor = 0.02350
- Length of duct = 100 feet

Energy audit and preliminary observation:

An energy audit was carried out on the air handling units (AHUs) in Hangar 101 at the BidP plant in Bangalore with the aim of identifying opportunities for energy savings and improving efficiency while maintaining optimal conditions for machine operation. The audit process encompassed data collection, physical inspection, data analysis, recommendations, and implementation. Key focus areas included assessing the layout of Hangar 101 and studying temperature profiles at various zones to gain insights into thermal conditions [6].

The audit revealed significant variations in fan efficiency, secondary fan efficiency, power consumption, and airflow between the AHUs on the North and South sides of the hanger. This data provided valuable information for pinpointing areas of improvement and optimizing the HVAC system. By addressing these variations, the plant can reduce operational costs, minimize energy waste, and enhance overall environmental sustainability [7].

Figure 1, a graphical representation of Hangar 101's layout and spatial organization, was analysed, alongside temperature profiles from different zones within the hangar. These temperature profiles provided critical insights into temperature distribution across various areas, helping to understand the thermal conditions prevailing in Hangar 101. This knowledge is vital for making informed decisions to maintain suitable working conditions for both equipment and personnel. The energy audit's comprehensive evaluation will serve as a roadmap for implementing energy-efficient measures and establishing best practices for ongoing facility management. By optimizing the AHUs and HVAC system, the BidP plant can achieve long-term energy savings, reduce its carbon footprint, and align with sustainability goals. The insights gained from the audit will contribute significantly to the plant's success in enhancing operational efficiency and maintaining a comfortable and environmentally friendly working environment in Hangar 101.

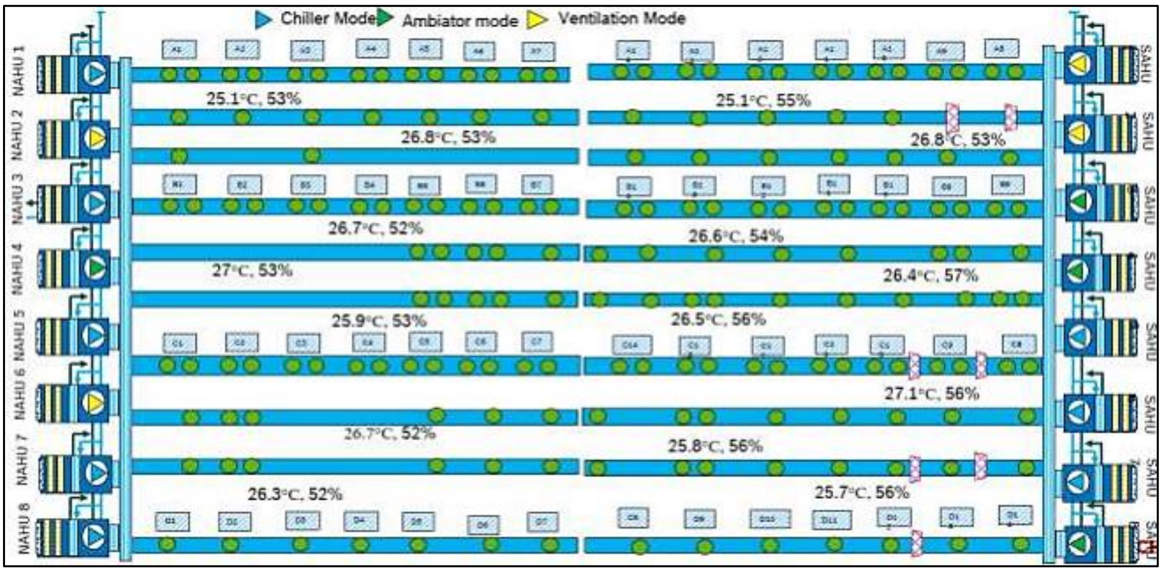


Figure 1. Layout of 101 Hanger and Temperature profile at various zones.

Operational parameters of AHU unit

The Table 1 displays crucial performance data for the air handling units (AHUs) in Hangar 101 at the BidP plant, Bangalore. Categorized as single fan (S AHU 01 to S AHU 04) or double fan (S AHU 05 to S AHU 08) systems, the AHUs' parameters such as space temperature, airflow, and power consumption are highlighted. For single fan AHUs, space temperature ranges from 135 to 36764, airflow from 35227 to 36764 m3/hr, and power consumption from 7.23 to 7.51 kW. For double fan AHUs, the space temperature is 115, with airflow ranging from 35238 to 36439 m3/hr and power consumption from 7.12 to 7.60 kW. Analysing these variables is instrumental in optimizing the HVAC system, achieving enhanced energy efficiency, and maintaining an ideal thermal environment in Hangar 101, leading to improved productivity and environmental sustainability. By leveraging these insights, the BidP plant can implement tailored solutions for optimal AHU performance and energy conservation, aligning with modern sustainability practices [8].

Table 1. AHU performance. (As per recent Energy Audit existing ahu performance).

S.N.	Description	Fan Type	Frequency (Hz)	CFM	Average Power Consumption	Air Flow Rate
1	S AHU 01	Single Fan	135	35227	7.27	141736
2	S AHU 02	Single Fan	135	35572	7.27	
3	S AHU 03	Single Fan	135	34173	7.27	
4	S AHU 04	Single Fan	135	36764	7.27	
5	S AHU 05	Double Fan	115	35228	7.35	143418
6	S AHU 06	Double Fan	115	35615	7.35	
7	S AHU 07	Double Fan	115	36439	7.35	
8	S AHU 08	Double Fan	115	36127	7.35	
Total				285154	7.31	285154

Table 2 presents the energy consumption from blower-type fans in hanger 101 at the BidP. plant in Bangalore. The table provides an overview of the overall energy consumption of these fans, which amounts to 56.95 kw and the below Figure 2 show the belt driven fan type which. was initially used in the air handling unit.

Table 2. Energy consumption from Blower type fans.

S.N.	**AHU No.**	**Blower type fan (old)**		
		Frequency (Hz)	***CFM***	***Power Consumption (kW)***
1	CP4 AHU 01	50	8039	9.20
2	CP4 AHU 02	50	7469	9.50
3	Line 5 AHU	50	9669	10.70
4	Line 6 AHU	50	14662	11.60
5	Line 7 AHU	50	9377	10.90
6	Lambda Sensors AHU	50	13104	5.05
Total				56.95

Figure 2. Belt driven blower fan type.

Work method statement involved in implementing axial fans for AHU unit

The project's primary objective is to conduct a comprehensive energy audit of the facility, meticulously assessing its energy consumption patterns and identifying areas for improvement. As part of the solution proposal, the adoption of energy-efficient axial fans is recommended to enhance overall energy performance. Through the energy audit, potential energy, and cost savings achievable by implementing the proposed fans will be estimated, providing valuable insights to the customer. Upon the customer's acceptance, a meticulous risk analysis and site observation will be conducted, ensuring the proposed changes align with safety and efficiency standards. During the implementation phase, the installation of the new fans will be carried out with utmost care, incorporating all necessary safety measures. The project's effectiveness will be verified through measurement and verification processes, objectively assessing the actual energy savings achieved after commissioning. Upon successful completion, the project will be handed over to the customer, accompanied by an in-depth energy-saving report. Additionally, training will be provided on system operation, monitoring, maintenance, troubleshooting, and safety practices. The block diagram demonstrates a well-organized and systematic approach, ensuring that energy efficiency is optimized, operational costs are reduced, and the facility's environmental sustainability is enhanced. Figure 3 depicts a block diagram illustrating the sequential steps involved in implementing energy-efficient axial fans in an air handling unit project. Figure 4 showcases the steps required for the implementation of electronically commutated fans and the process of fan selection [9].

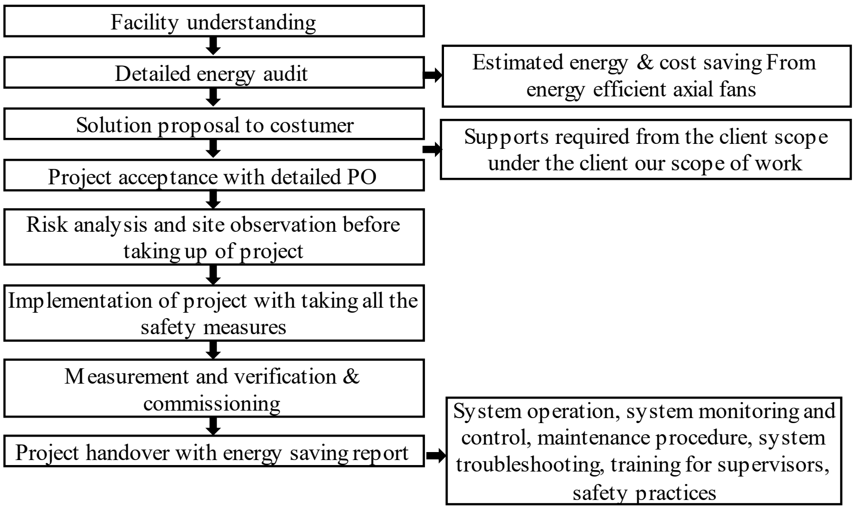


Figure 3. Flow chart of steps involved in the operation of the Air Handling Unit

HVAC systems that exclusively use static pressure lose out on the opportunity to operate at efficiency levels beyond 90%. Fans that use both the static and dynamic pressures are necessary to create the most energy-efficient ventilation system. Plug and centrifugal fan efficiency is determined entirely based on static pressure. This is due to the systems' inability to make use of the dynamic pressure, which they blatantly discard. Axial fans can achieve efficiencies of 90% because of their design, which makes use of both static and dynamic pressures. As a result, their efficiencies are based on the total pressure. Figure 5 and Figure 6 demonstrates how axial fans utilize both static pressure and dynamic pressure to deliver airflow.

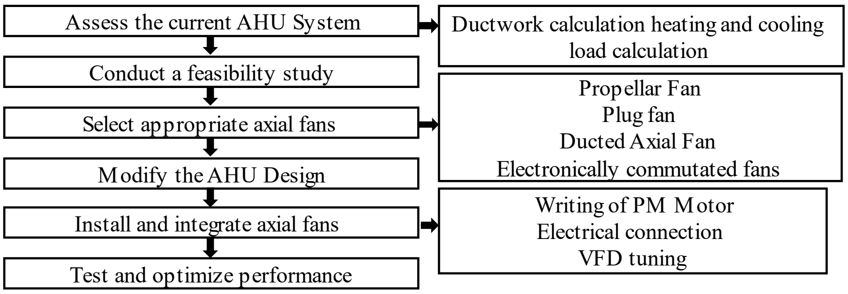


Figure 4. Block diagram to represent the steps involved in implementing axial fans.

The depicted Figure illustrates how axial fans leverage both static pressure and dynamic pressure to enhance efficiency. When the axial fan operates, it draws air into the system, generating a combination of static and dynamic pressure. The static pressure results from the resistance the fan faces while pushing the air through the system, particularly against obstructions like filters and ducts. Simultaneously, the axial fan creates dynamic pressure by imparting velocity to the air, which increases its kinetic energy. This combined static and dynamic pressure allows the fan to efficiently circulate air and deliver optimal performance. By utilizing both pressure components, the axial fan achieves higher efficiency in various applications, such as ventilation, cooling, and air circulation, contributing to energy savings and improved system performance.

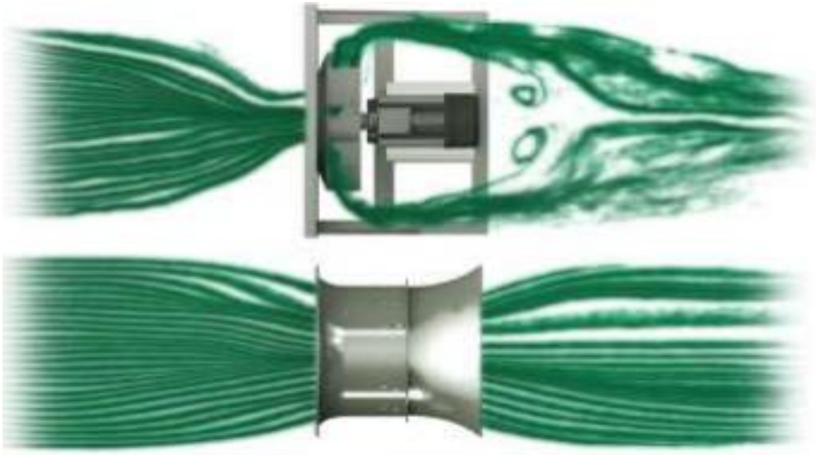


Figure 5. Axial fans utilization of static pressure and dynamic pressure.

Figure 6 illustrates the horizontal and vertical mounting configurations of axial fans in both top and side views. The horizontal mounting orientation shows the axial fan positioned parallel to the ground, with the fan blades rotating in a horizontal plane. In contrast, the vertical mounting arrangement displays the axial fan mounted perpendicular to the ground, with the fan blades rotating in a vertical plane. These different mounting options offer flexibility in fan installation, enabling them to be effectively integrated into various HVAC systems, cooling applications, and industrial processes. The figure provides valuable visual insights into the possible orientations of axial fans, aiding in their appropriate selection and placement for optimal airflow and system performance.

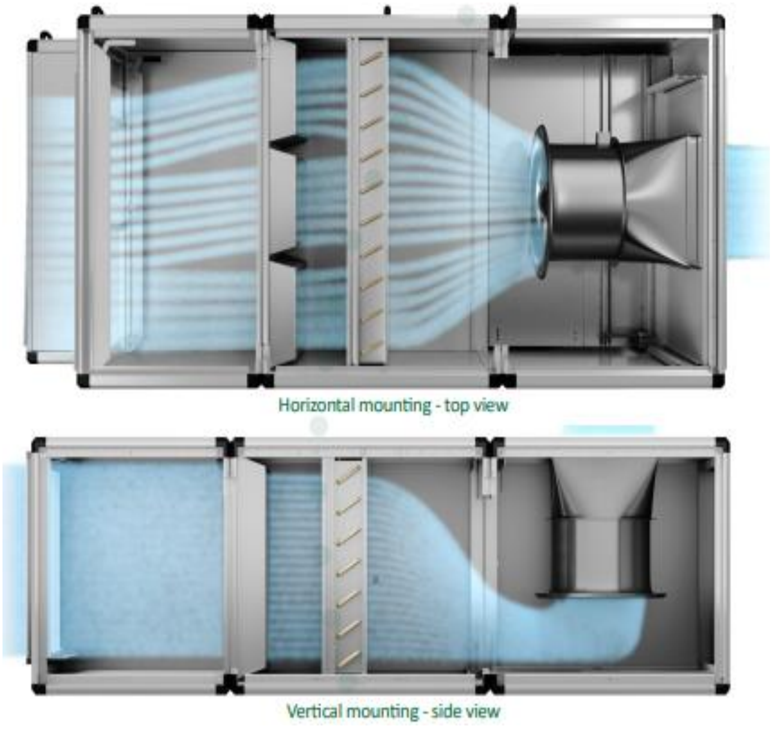


Figure 6. Depicts the horizontal and vertical mounting of axial fans in top and side view.

In the comparison of various fans used in air handling units (AHUs), the axial flow fan emerges as the most efficient and reliable option. It achieves a total efficiency of approximately 85%, providing smooth airflow with minimal pressure loss. On the other hand, centrifugal fans, plug fans, and 4 x EC plug fans experience turbulence and generate noise, resulting in lower efficiency levels.

Due to their distinct benefits, axial flow fans are frequently employed in air handling units (AHUs), including:

1. *High airflow capacity:* Axial flow fans are perfect for applications where a high airflow capacity is required because they can move huge volumes of air through an AHU.
2. *Reduced noise levels:* Axial flow fans are a great choice for usage in noise-sensitive locations because they generate comparatively low noise levels when compared to other types of fans.
3. Axial flow fans are an energy-efficient solution for air handling systems since they require relatively little power to run.
4. Axial flow fans are extremely simple to maintain and repair, which minimises downtime and repair expenses.
5. Axial flow fans are often more compact and smaller than other types of fans, which makes them simpler to install in confined locations.
6. *Flexibility:* Axial flow fans may be easily modified to meet changing airflow requirements and are suitable for a wide range of airflow applications.

Axial flow fans are a great option for air handling equipment when factors like high airflow capacity, low noise levels, energy efficiency, and simple maintenance are crucial. They are a dependable and affordable solution for air handling systems in a few industries and applications. Figure 7 illustrates the total efficiency achieved with EC+ fans, including the motor and variable frequency drive (VFD). The efficiency is measured at 85 percent, indicating the effectiveness of the EC+ fan system in terms of energy utilization and performance.

Figure 7. Total Efficiency of EC + fans

Solution architecture of AI model project

Figure 8 presents the complete solution architecture for the implementation of an AI model in clean rooms. This architecture diagram illustrates the comprehensive design and structure of the system required for deploying and utilizing the AI model within the clean room environment.

The figure highlights the various components and their interconnections within the solution architecture. It provides a visual representation of how the AI model is integrated into the clean room infrastructure to enable intelligent decision-making and automation.

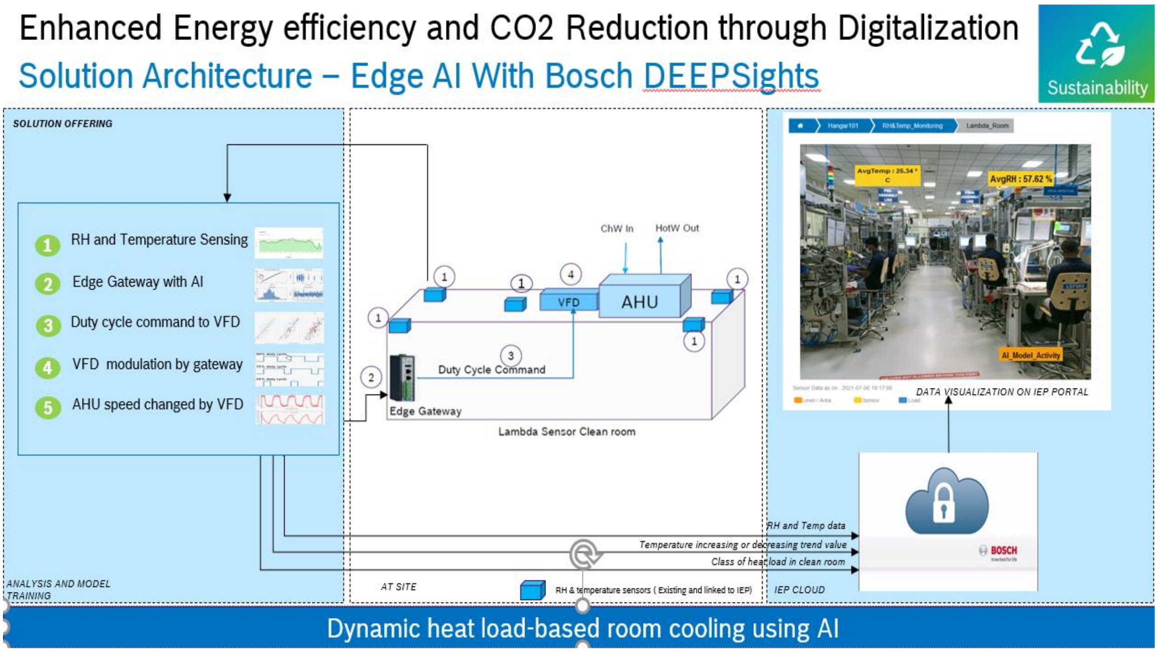
The solution architecture for the problem of controlling AHU in clean rooms of a manufacturing unit involves implementing an AI model to optimize energy efficiency and reduce CO_2 emissions.

The architecture consists of the following components and steps:

1. *Sensor Integration:* Install temperature and RH sensors (Mosibus sensors) in the clean rooms to collect real-time data on temperature and humidity levels.
2. *Data Collection and Preprocessing:* Collect sensor data from the installed sensors and perform data preprocessing to clean and prepare the data for further analysis. This may involve removing outliers, handling missing values, and normalizing the data.

3. *Decision Tree Algorithm:* Apply a decision tree algorithm to the preprocessed sensor data to analyze the temperature and humidity trends and classify the heat load in the clean room. The decision tree algorithm will help determine the appropriate control actions for the AHU based on the current conditions.
4. *Edge Gateway and VFD Control:* Deploy an edge gateway device that receives the classified heat load information from the decision tree model. The edge gateway communicates with the Variable Frequency Drive (VFD) of the AHU to modulate the AHU's speed and control the airflow rate accordingly. This enables dynamic control of the AHU based on the detected heat load.
5. *Data Visualization and Cloud Service:* Transmit the real-time temperature, RH, and heat load trend data, along with the AHU control commands, to the Bosch cloud service. The cloud service provides a platform for data visualization and further processing of the collected data for future use cases.
6. *Energy Efficiency and CO^2 Emission Optimization:* Utilize the analyzed data and insights from the cloud service to optimize the AHU's operation and control strategy. This optimization aims to minimize energy consumption, reduce CO_2 emissions, and ensure efficient temperature and RH control in the clean rooms.

By implementing this solution architecture, the manufacturing unit can achieve better control of the AHU's operation in response to changing heat loads, leading to improved energy efficiency, reduced CO_2 emissions, and optimized temperature and RH conditions in the clean rooms. The data visualization and cloud services provide valuable insights for ongoing monitoring, analysis, and future enhancements to the AHU control system.



Enhanced Energy efficiency and CO2 Reduction through Digitalization

Solution Architecture – Edge AI With Bosch DEEPSights

Dynamic heat load-based room cooling using AI

Figure 8. Complete solution architecture of AI model project.

RESULTS

The energy audit indicated significant discrepancies in the performance of single fan (S AHU 01 to S AHU 04) and double fan (S AHU 05 to S AHU 08) systems, with varying parameters for space temperature, airflow, and power consumption. For single fan AHUs, the space temperature ranged from 135 to 36764°C, airflow from 35227 to 36764 m^3/hr, and power consumption from 7.23 to 7.51 kW. Double fan AHUs exhibited a space temperature of 115°C, airflow from 35238 to 36439 m^3/hr, and power consumption from 7.12 to 7.60 kW.

DISCUSSION

The findings reveal that axial flow fans outperform centrifugal fans in terms of efficiency, noise reduction, and maintenance simplicity. The integration of AI technology in controlling AHUs enhances energy management and operational efficiency, enabling real-time adjustments based on environmental conditions. The proposed AI-driven solution architecture optimizes the operation of AHUs by incorporating sensor data to dynamically control airflow and temperature, resulting in reduced energy consumption and CO_2 emissions.

CONCLUSION

The integration of EC+ fans with Variable Frequency Drives (VFDs) and Permanent Magnet (PM) motors presents a significant advancement in enhancing the energy efficiency and performance of HVAC systems. This study, anchored in an extensive energy audit conducted at the BidP plant in Bangalore, reveals critical insights into the operational parameters of air handling units (AHUs) within Hangar 101. The audit findings highlighted notable discrepancies in fan efficiency, power consumption, and airflow rates, prompting a reevaluation of existing HVAC strategies.

Through rigorous calculations of heating and cooling loads, airflow rates, and pressure drops, this research established a comprehensive understanding of the thermal dynamics within clean rooms. The results demonstrate that axial flow fans offer superior efficiency compared to traditional centrifugal fans, achieving an efficiency of approximately 85%. This efficiency translates to reduced energy consumption, lower operational costs, and a smaller carbon footprint.

The proposed solution architecture, incorporating an AI model for real-time control of AHUs based on sensor data, further optimizes energy usage by dynamically adjusting to varying heat loads. This innovative approach not only ensures optimal indoor climate conditions but also aligns with sustainability goals by minimizing energy waste.

In conclusion, the findings of this research underscore the importance of integrating advanced technologies and practices in HVAC design and operation. By adopting energy-efficient systems, industries can achieve significant cost savings while contributing to environmental sustainability. The insights from this study provide a valuable roadmap for future implementations in similar settings, paving the way for enhanced operational efficiency and sustainable facility management.

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