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Turbine Ventilator Layout Design for a Food Product Logistics Warehouse

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A B S T R A C T

This study aims to determine the required number of turbine ventilators and design an optimal layout for a food logistics warehouse, taking into account air circulation, temperature, relative humidity, airflow distribution, and heat reduction. The research employs an experimental method combined with quantitative analysis. Measurements were taken at 17 points using a multi-sampling approach over a three-day period. The recommended air exchange rate for the warehouse is 2–4 air changes per hour (ACH), in accordance with the Axair Industrial Ventilation Guide and HVAC standards. Several ventilator layout alternatives were developed and evaluated using a Performance-Based Design (PBD) approach, considering ACH values, temperature, relative humidity, airflow distribution, and the effectiveness of heat reduction. The results indicate that the current ventilation system produces an airflow rate of 3,691.01 m³/hour, equivalent to an ACH of 0.37 per hour. The average air velocity was recorded at 0.089 m/s, with an average temperature of 30.13°C and an average relative humidity of 77%; these conditions reflect inadequate air circulation and an environment that exceeds recommended limits. Based on the ACH calculations, 12 turbine ventilators are required to achieve 2 ACH, 19 units for 3 ACH, and 25 units for 4 ACH. The PBD evaluation identifies the 19-unit configuration as the optimal design, as it effectively balances improved air circulation, airflow distribution, temperature and humidity control, and implementation efficiency. This configuration is expected to enhance ventilation performance and support more suitable storage conditions for packaged food products within the warehouse.

1. INTRODUCTION

Food logistics warehouses store products such as snacks and packaged beverages that are sensitive to high temperatures and humidity, as these conditions can degrade quality and damage packaging. (Septiati et al., 2024).

Uneven natural ventilation can lead to heat and humidity issues, as occurred at a logistics warehouse in Batam, where approximately 253 cartons of packaged beverages were damaged in October 2025 (High humidity levels can also damage the packaging, while high temperatures can reduce the product's nutritional content (Soolany et al., 2024). These conditions pose a risk of reducing product quality during storage. Observations indicate that increased humidity can cause packaging cartons to lose their structural integrity, while excessively high temperatures can diminish the product's nutritional content (Nurhidayat & Adiluhung, 2021). Ventilation requirements can be determined using Air Changes per Hour (ACH), whereas Performance-Based Design (PBD) is used to establish performance and air distribution (Abdullah & Alibaba, 2022). Turbine ventilators serve as a passive ventilation alternative that utilizes wind energy and the chimney effect to exhaust hot air and increase the air change rate (ACH) (Yolanda et al., 2022). A turbine ventilator is a passive ventilation system that utilizes wind energy and the stack effect to exhaust hot air from a building. This system has the potential to increase the air change rate per hour (ACH), particularly in buildings with large volumes (Rosminahar et al., 2025).

The effectiveness of the ventilators is influenced by building conditions, the environment, and the number and configuration of the units; therefore, technical calculations are required (Winardo kennardy, 2023). To address air circulation issues in a food logistics warehouse, this study proposes a solution involving the layout design of turbine ventilators

acting as a passive natural ventilation system to enhance air exchange and distribution within the facility. The research begins by calculating the required number of ventilators based on a target Air Change per Hour (ACH) rate, taking into account the warehouse volume and the capacity of individual ventilators. Subsequently, various alternatives regarding the quantity and placement of roof-mounted turbine ventilators are designed to determine the configuration best suited to the warehouse's specific conditions. Each alternative is then evaluated using a Performance-Based Design (PBD) approach, considering factors such as ACH values, temperature, humidity, air distribution, heat exhaust capability, and cost-efficiency. Through this process, the study aims to determine the necessary number of ventilators, formulate layout alternatives, and identify the optimal configuration to improve the warehouse's air circulation performance. Ultimately, the research findings are expected to provide design recommendations for turbine ventilators that effectively enhance air exchange and uniformity, assist in temperature and humidity control, and ensure efficiency in terms of implementation and cost.

2. LITERATURE REVIEW

2.1. *The Role of the Logistics Warehouse as a Product Storage Facility*

Food logistics warehouses require appropriate environmental conditions, as suboptimal temperature and humidity can degrade product quality and damage packaging (Fathurrohman et al., 2023). Poor air circulation can increase temperature and humidity, as well as trigger the growth of microorganisms and the development of unpleasant odors (Fahmi Ivannuri et al., 2022).

Ventilation helps bring in fresh air and remove heat and moisture, thereby maintaining stable conditions within the warehouse (Noldy Tumembow & Siwi, 2021). Ventilator turbines serve as an energy-efficient alternative by utilizing wind energy to reduce heat and humidity (ismanto agustino christian & kurniawan arif, 2022). Installing ventilator turbines can help maintain product quality and improve worker comfort (Harun et al., 2018).

2.2. *Storage Environment Conditions*

Temperature and humidity affect product quality, productivity, and warehouse operational efficiency (Raffi Anton Pratama & Raditya Alvin Dea Rachmadi, 2022). The ventilator design needs to be adjusted in terms of quantity, diameter, and installation position to optimize air distribution (Saputra & Arsianti, 2021). Positioning ventilators evenly while taking into account the spacing between units, wind direction, and air inlets can improve circulation and reduce dead zones (Septiati et al., 2024). Therefore, the design of the turbine ventilator system must take into account the number and placement of units to ensure optimal maintenance of the warehouse's temperature, humidity, and air quality.

2.3. *Impact of Ventilator Layout on Productivity*

Warehouse layout and ventilation placement need to take into account air circulation, temperature, and humidity. Overcrowded shelving, high stacks of goods, and uneven ventilation can impede airflow (Hari Purwoko & Noor Cholis Idham, 2019).

Poor air circulation can lead to temperature and humidity instability, posing a risk of accelerated product quality degradation, mold and bacterial growth, and packaging damage (Aulia et al., 2021). Hot and humid warehouse conditions can also reduce worker comfort and productivity. Therefore, the warehouse layout needs to be adjusted regarding ventilation placement to create better air distribution and working conditions (Nurhaliza Hariyanti et al., 2025).

2.4. *Measurement of thermal environmental conditions and ventilation standards*

Measurements of temperature, relative humidity (RH), and air velocity were conducted in accordance with the ISO 7726:1998 standard at a height of 1.1–1.7 m, utilizing a multiple-point sampling method to calculate the air flow rate (Q) and air change rate (ACH). Ventilation evaluation was based on SNI 03-6572-2001, while ACH requirements were determined using the Axair Industrial Ventilation Guide and HVAC standards, which specify a range of 2–4 ACH for dry storage warehouses.

2.5. *Circulation and Measurement Process*

Air circulation plays a crucial role in maintaining the quality, safety, and shelf life of food products in warehouses by controlling temperature, humidity, and air quality. The primary functions of air circulation include:

a. Control the room temperature
Air circulation helps distribute air evenly and prevents the formation of hot spots that can accelerate product spoilage.

b. Controlling humidity
Air circulation helps control humidity to prevent mold and bacteria growth, as well as packaging damage.

c. Maintaining air quality and cleanliness
Ventilation helps reduce airborne dust, particles, and microorganisms, thereby preventing contamination and supporting food safety.

d. Improving worker comfort and health
Proper airflow reduces heat and stuffiness, creating a more comfortable work environment and supporting worker productivity.

Methods for controlling air circulation in food warehouses include:

a. Using natural ventilation
Utilize windows, openings, or cross-ventilation to admit fresh air and naturally exhaust hot air.

b. Using mechanical ventilation
Using fans, blowers, or HVAC systems to regulate airflow in a more stable and controlled manner.

c. Memantau suhu dan kelembapan
Periodically measure temperature and humidity to ensure environmental conditions meet food storage requirements.

d. Adjusting ventilation capacity to the size of the warehouse
Ventilation capacity must be adjusted according to the warehouse's area and volume to ensure effective air exchange. Proper circulation arrangements help maintain temperature, humidity, product quality, and workplace comfort.

2.6. *Comparison of Research Discussion*

Table 1. Comparison of research discussions

No.	Peneliti (Tahun)	Fokus & Metode	Hasil Utama	Kesenjangan
1	Yolanda et al. (2022)	ACH and natural ventilation; anemometer measurements.	ACH can be used to evaluate air exchange.	Does not address the number and layout of turbine ventilators.
2	Shafa et al. (2023)	Ventilation and thermal comfort; measurements of temperature, humidity, and airflow.	Natural ventilation affects airflow patterns.	Does not use ACH as a design basis.
3	Hermawan et al. (2023)	Natural ventilation and thermal conditions; measurements of temperature, humidity, and CO_2.	Ventilation influences the thermal conditions of a space.	Does not address the layout of turbine ventilators.
4	Dumingu et al. (2023)	Ventilation and thermal comfort in classrooms.	Space conditions affect thermal comfort.	The subject and ventilation requirements differ from those of food warehouses.
5	Sasono (2021)	IoT-based temperature and humidity control for storage spaces.	Temperature and humidity are important for storage.	Focuses on pharmaceutical monitoring rather than ventilation design.
6	Ramli et al. (2025)	Thermal comfort and air quality in tropical buildings.	Natural ventilation affects temperature, humidity, and air quality.	Does not address food warehouses or turbine ventilators.
7	Putra et al. (2026)	ACH and air quality in natural ventilation.	Increasing ACH reduces certain air pollutants.	Focuses on air quality rather than warehouse ventilation design.

3. METHODOLOGY

3.1. *Research Object and Location*

This study was conducted at a food logistics warehouse in Batam City, focusing on temperature, humidity, air velocity, as well as the specifications and layout of turbine ventilators. The warehouse has dimensions of 57.43 m × 23 m × 7.5 m and a volume of 9,905.68 m³.

3.2. *Types and Sources of Data*

The research data consists of primary and secondary data. Primary data were obtained through measurements of temperature, relative humidity (RH), and air velocity using a multi-sampling method.

Secondary data include warehouse dimensions, ventilation characteristics, ventilator turbine specifications, thermal environment standards, and wind speed data for Batam City, which served as the basis for the design.

3.3. *Data collection techniques*

Data collection was conducted at 17 locations (G1–G17) over three days, with three sessions per day, using a multiple-sampling method. The measured parameters included temperature, relative humidity (RH), and air velocity, yielding a total of 153 air velocity data points. Instrument placement followed the ISO 7726 standard.

3.4. *Research Instruments*

The instruments used were a Benetech GM816 anemometer and thermo-hygrometer to measure air velocity, temperature, and relative humidity at each observation point.

3.5. *Data Processing*

The data were processed by calculating the average temperature, relative humidity (RH), and air velocity, after which their adequacy was tested based on confidence level and precision. The results were compared against reference values to assess the warehouse's environmental conditions.

3.6. *Calculation of Airflow Rate and Air Changes*

The actual airflow rate is calculated based on air velocity and the cross-sectional area of the flow using the following equation:

$$Q = v \times A$$

Where:

(Q) is the airflow rate (m³/s),
(v) is the air velocity (m/s),
(A) is the cross-sectional area of the flow (m²).

The airflow rate is then converted to m³/h. Subsequently, the air change rate (Air Changes per Hour or ACH) is calculated based on the airflow rate and the warehouse volume using the equation:

$$(Q \times 60) / V$$

Where:

(ACH) is the number of air changes per hour,
(Q) is the airflow rate (m³/min),
(V) is the warehouse volume (m³).

This actual ACH value serves as the basis for determining the warehouse's additional ventilation requirements.

3.7. *Design of Ventilator Layout Alternatives*

The design process yielded three ventilator layout alternatives Alternatives I, II, and III. Each alternative takes into account the number of units, placement, spacing between units, and ventilation coverage, enabling a comparison based on

air exchange capacity and the uniformity of air distribution. Ventilator placement is tailored to the warehouse geometry to ensure effective air distribution throughout the area.

3.8. *Evaluation of Layout Alternatives*

Each alternative was evaluated based on air exchange requirements, the number of ventilators, area coverage, placement, and design efficiency. The best alternative was selected based on a balance between airflow performance, uniform air distribution, and the number of units.

4. RESULTS AND DISCUSSION

4.1. *Current Warehouse Conditions*

Determining the condition of the warehouse involves measuring the warehouse volume, calculating the actual airflow rate, and calculating the Air Changes per Hour.

a. Warehouse Volume Calculation

The warehouse volume is calculated using the equation:

$$V = P \times L \times T \quad (1)$$

Where:
V = Warehouse volume (m³)
P = Warehouse length (m) = 57.43 m
L = Warehouse width (m) = 23 m
T = Warehouse height (m) = 7.5 m
Then:
V = 57.43 × 23 × 7.5
V = 9,905.68 m³
Thus, the volume of the logistics warehouse is 9,905.68 m³.

b. Calculation of Actual Warehouse Air Flow Rate

The warehouse airflow rate is calculated based on the natural wall ventilation to determine the resulting rate of airflow.

Calculation of Natural Ventilation Area

The warehouse features rectangular natural ventilation openings measuring 80 cm × 40 cm (equivalent to 0.8 m × 0.4 m).

The area of a natural ventilation opening is calculated using the equation:
$A1 = l \times w$
$A1$ = 0.8 × 0.4
$A1$ = 0.32 m²
Number of available ventilation openings:
Number of walls = 6 sides
Number of openings per wall = 6 units
Total openings = 6 × 6 = 36 units
Total ventilation area:
A = 36 × 0.32
A = 11.52 m²
Thus, the total available natural ventilation area is 11.52 m².

Calculation of Air Flow Rate (Q)

Based on measurements taken over three days, the average air velocity was determined to be:
v = 0.089 m/s
Since the air flow rate is calculated in units of m³/h,the air velocity is converted as follows:
v = 0.089 m/s × 3600 s/h
v = 320.4 m/h
The air flow rate is calculated using the equation:
$Q = V \times A$
Where:
Q = Air flow rate (m³/h)
V = Air velocity (m/h)
A = Ventilation area (m²)
Thus:
Q = 320.4 × 11.52
Q = 3,691.01 m³/h
Therefore, the actual air flow rate in the logistics warehouse is 3,691.01 m³/h.

Actual Air Change Per Hour (ACH) Calculation

The ACH value is calculated using the equation:
ACH = Q/V
Where:
ACH = Air Changes per Hour (times/hour)
Q = Airflow rate (m³/hour)
V = Warehouse volume (m³)
Thus:
ACH = 3,691.01 / 9,905.68
ACH = 0.37 times/hour
The actual ACH value for the logistics warehouse is 0.37 times/hour.

Measurement results indicate that air circulation conditions in the food product logistics warehouse are not yet optimal (Rusmiatmoko et al., 2018). Parameters regarding current conditions, obtained from the measurements, are presented in Table 2.

Table 2. Actual ACH – Logistics Warehouse

Parameter	Actual Condition
Average air velocity	0.089 m/s
Average air temperature	30.13 °C
Relative humidity	77%
Actual ACH	0.37 times/hour

(Source: Observational Data, 2025)

Based on Table 2, the average airflow velocity of 0.089 m/s and the ACH value of 0.37 air changes per hour indicate that the air exchange rate remains low. The temperature of 30.13°C and humidity of 77% also indicate that environmental conditions are not yet optimal.

4.2. *Turbine Ventilator Requirements*

Calculation results indicate an actual ACH value of 0.37 air changes per hour, which remains below the warehouse ventilation requirement of 49,533–79,253 m³/h based on a target of 2–4 ACH. Given that 24-inch (60 cm diameter) aluminum turbine ventilators have a capacity range of 1,188–4,393 m³/h, an average capacity of 1,600 m³/h was used as the basis for calculating ventilator requirements for targets of 2, 3, and 4 ACH, as follows:
2 ACH = 19,811.36 m3/hour
Number of units = 19,811.36/1600 = 12.38 ≈ 12 units
3 ACH = 29,717.04 m3/hour
Number of units 29,717.04/1600 = 18.57 ≈ 19 units
4 ACH = 39,622.72 m3/hour
Number of units 39,622.72/1600 = 24.76 ≈ 25 units

The calculation results for ventilator requirements are based on the target Air Changes per Hour (ACH). The capacity of the turbine ventilator used in this study was set at 1,600 m³/hour. The results of the calculation of ventilator requirements based on the target ACH are presented in

Table 3. Ventilator Requirements Based on Target ACH

Target ACH	airflow requirement (m³/h)	number of ventilators
2 ACH	19.811,36	12 units
3 ACH	29.717,04	19 units
4 ACH	39.622,72	25 units

(Source: Data processing)

Based on Table 3, the number of ventilators required increases with the ACH target: 12 units for 2 ACH, 19 units for 3 ACH, and 25 units for 4 ACH. These results serve as the basis for developing alternative layout configurations for the ventilator turbines.

Ventilator turbines utilize wind energy to exhaust air from within the building. Installing them on the roof can improve air circulation and reduce the influx of hot air. (Noldy Tumembow & Siwi, 2021).

4.3. *Comparison of Design Alternatives*

A comparison of various alternatives was conducted based on the number of ventilators, airflow capacity, ACH values, and their compliance with the ACH range used in this study.

Alternative Design I

This alternative design utilizes twelve aluminum turbine ventilators with a 24-inch diameter, installed along the center of the warehouse roof. This option is designed to enhance air exchange at a relatively lower investment cost compared to other options. The model estimates and calculations are detailed below.

Additional ventilator capacity:
Capacity formula for a single ventilator
Q = 1,600 m³/h
Additional ventilator capacity
Q = 2 × 1,600
Q = 3,200 m³/h
Total airflow rate
Q = 19,811.36 + 3,200
Q = 23,011.36 m³/h
ACH value
ACH = 23,011.36 / 9,905.68
ACH = 2.32 air changes per hour

Alternative I increases the ACH from 0.37 to 2.32 air changes per hour following the installation of 12 turbine ventilators, resulting in an airflow rate of 23,011.36 m³/h. These results indicate improved air circulation and meet the minimum ventilation requirement of 2 ACH.

Alternative Design II

Alternative II employs 24-inch diameter aluminum turbine ventilators, evenly spaced across the warehouse roof, to enhance air circulation capacity and distribution while helping to regulate indoor temperature and humidity, as follows:

Additional ventilator capacity
Q = 3 × 1,600
Q = 4,800 m³/h
Total air flow rate
Q = 29,717.04 + 4,800
Q = 34,517.04 m³/h
ACH value = 34,517.04 / 9,905.68
ACH = 3.48 air changes per hour

Alternative II results in an increase in the ACH value from 0.37 air changes per hour under existing conditions to 3.48 air changes per hour following the installation of 19 turbine ventilators. This represents an increase of 3.11 air changes per hour, or approximately 840.54%, compared to the initial state. Total air flow also rises to 34,517.04 m³/h,

Resulting in superior air distribution within the warehouse compared to both existing conditions and Alternative I. The resulting ACH value meets the standard requirement for warehouse air exchange rates of 2–4 air changes per hour.

Alternative Design III

Alternative III utilizes eight aluminum turbine ventilators, each with a 24-inch diameter, installed evenly across the warehouse roof. This alternative is designed to achieve a higher air exchange rate, minimize stagnant air zones, and ensure more uniform airflow distribution throughout the storage area. The model estimates and calculations are detailed below.

Additional ventilator capacity:
Additional ventilator capacity
Q = 4 × 1,600
Q = 6,400 m³/h
Total airflow rate
Q = 39,622.72 + 6,400
Q = 46,022.72 m³/h
ACH value = 46,022.72 / 9,905.68
ACH = 4.64 air changes per hour

Alternative III increases the ACH from 0.37 to 4.64 air changes per hour, with a total airflow of 46,022.72 m³/h. This alternative yields the best air circulation and distribution compared to Alternatives I and II. The results of the comparison are presented in Table 4.

Table 4. Comparison of Design Alternatives

Parameters	actual conditions	Alternative I	Alternative II	Alternative III
number of ventilators	0	12 units	19 units	25 units
Additional ventilator capacity	–	3.200 m³/h	4.800 m³/h	6.400 m³/h
Total airflow	–	23.011,36 m³/h	34.517,04 m³/h	46.022,72 m³/h
ACH	0,37	2,32	3,48	4,64
ACH Requirements	Does not meet the	fulfil	fulfil	Exceeds the limit

(Source: Data processing)

Based on Table 4, the current condition has an ACH value of 0.37 air changes per hour, which does not meet the required specifications. Alternatives I, II, and III yield ACH values of 2.32, 3.48, and 4.64, respectively.

4.4. *Turbine Ventilator Layout Analysis*

In addition to the number of units, ventilator layout is also important in the design of a ventilation system. Placing ventilators on the roof helps exhaust the hot, humid air that accumulates in the upper part of the building (Sahabuddin Latif, 2020). Even distribution of units also helps reduce areas with poor air circulation.

Table 5. Comparison of Ventilator Layouts

Alternative	Number of Ventilators	Vertical distance	Transverse distance
Alternative I	12 units	±11,46 m	±5,75 m
Alternative II	19 units	±9,55 m	±4,60 m
Alternative III	25 units	±9,55 m	±3,83 m

Alternative II utilizes 19 units spaced approximately 9.55 m apart longitudinally and 4.60 m apart transversely, resulting in a more uniform air distribution and helping to reduce stagnant zones (Sahabuddin Latif, 2020). The placement of ventilators requires consideration of their spacing and distribution to ensure even airflow.

4.5. *Evaluation and Selection of Alternatives*

The selection of the ventilator turbine design employs a Performance-Based Design (PBD) approach based on five parameters: ACH, temperature, RH, airflow distribution, and heat reduction effectiveness. Efficiency and implementation costs are also considered in determining the best alternative. The parameters used include:

A. Air circulation (Air Changes per Hour/ACH).
B. Air temperature.
C. Relative Humidity (RH).
D. Airflow distribution.
E. Ventilation effectiveness for heat reduction.

Air Circulation

The evaluation of air circulation alternatives is based on the Air Change per Hour (ACH) values for each design option. A higher ACH value indicates a greater capacity for the ventilation system to exchange air within the warehouse (Rinanda et al., 2021).

Table 6. Comparison of Air Circulation

Parameter	Existing	Alternative I	Alternative II	Alternative III
Number of ventilators (units)	-	2	3	4
Additional air flow rate (m^3/h)	-	1,95	3,11	4,27
Total air flow rate (m^3/h)	3.691,01	23.011,36	34.517,04	46.022,72
ACH (time/h)	0,37	2,32	3,48	4,64
Circulation category	Very low	Enough	Good	Very good

Increasing the number of ventilator turbines raised the air circulation rate and ACH value, shifting the initial condition of 0.37 air changes per hour to 2.32 ACH for Alternative I, 3.48 ACH for Alternative II, and 4.64 ACH for Alternative III. This increase resulted from a higher airflow capacity (Q) within a constant warehouse volume. (Abdul Salam Rasheed, 2018). This demonstrates that increasing ventilation capacity directly impacts indoor air exchange (Abdul Salam Rasheed, 2018).

Based on air circulation parameters, Alternative II with a value of 3.48 ACH is considered the most suitable as it falls within the required ventilation range of 2–4 ACH, whereas Alternative III exceeds this upper limit. Therefore, Alternative II is selected as the most appropriate option regarding air circulation (Timothy Dwyer, 2022).

Table 7. Air circulation speed categories

Air Speed (m/s)	Category
0,15–0,25	Meets standards
0,10–<0,15	Nearly meets
0,05–<0,10	Partially meets
<0,05	Does not meet

Temperature Analysis

Evaluation of alternatives on temperature was carried out to determine the ability to reduce heat accumulation in the warehouse. The lower the temperature produced, the better the performance of the ventilation system (Shafa et al., 2023).

At this stage, a temperature analysis is conducted on the alternativs, as follows:

Alternatif Turbin I

Temperature drop difference based on ISO

$\Delta T = T_{outdoor} - T_{indoor}$

$\Delta T = 28°C - 20°C = 8°C$

Conversion of airflow to per-second units

$V = (23{,}011.36\ m^3/hour) / (3{,}600\ seconds)$

$V = 6.39\ m^3/second$

Air density and heat capacity values

Air density (ρ) = 1.2 kg/m^3

Air heat capacity (Cp) = 1,005 J/kg

Calculating total heat transfer energy (Qv)

$Qv = V \times \rho \times Cp \times \Delta T$

$Qv = 6.39 \times 1.2 \times 1{,}005 \times 8$

$Qv = 61{,}650.72$ Watts

Where:

Qv (heat load)

V (airflow rate per second)

ρ (air density)

Cp (heat capacity)

Rearranging the formula (isolating variable ΔT)

$\Delta T = Qv / (V \times \rho \times Cp)$

$\Delta T = 61{,}650.72 / (6.39 \times 1.2 \times 1{,}005)$

$\Delta T = 61{,}650.72 / 7{,}706.34$

$\Delta T = 8°C$

The resulting air temperature drop is approximately 8°C, based on the ISO range of 20°C – 28°C.

The final result is 20°C with a heat dissipation power of 61,650.72 Watts.

Alternatif Turbin II

Temperature drop difference based on ISO

$\Delta T = T_{outside} - T_{inside}$

$\Delta T = 28°C - 20°C = 8°C$

Conversion of airflow to seconds

$V = (34{,}517.04\ m^3/h) / (3600\ seconds)$

$V = 9.58\ m^3/s$

Air density and heat capacity values

Air density (ρ) = 1.2 kg/m³

Air heat capacity (Cp) = 1,005 J/kg

Calculating total heat transfer energy (Qv)

$Qv = V \times \rho \times Cp \times \Delta T$

$Qv = 9.58 \times 1.2 \times 1{,}005 \times 8$

$Qv = 92{,}427.84$ Watts

Where:

Qv (heat load)

V (airflow rate per second)

ρ (air density)

Cp (heat capacity)

Rearranging the formula (isolating variable ΔT)

$\Delta T = Qv / (V \times \rho \times Cp)$

$\Delta T = 92{,}427.84 / (9.58 \times 1.2 \times 1{,}005)$

$\Delta T = 92{,}427.84 / 11{,}553.48$

$\Delta T = 8°C$

The resulting air temperature drop is approximately 8°C, based on the ISO range of 20°C – 28°C

The final result is 20°C with a heat dissipation power of approximately 92,427.84 Watts

Turbine Alternative III

Temperature drop difference based on ISO

$\Delta T = T_{outside} - T_{inside}$

$\Delta T = 28°C - 20°C = 8°C$

Conversion of airflow to seconds

$V = (46{,}022.72\ m^3/h) / (3600\ seconds)$

$V = 12.78\ m^3/s$

Air density and heat capacity values

Air density (ρ) = 1.2 kg/m³

Air heat capacity (Cp) = 1,005 J/kg

Calculating total heat transfer energy (Qv)

$Qv = V \times \rho \times Cp \times \Delta T$

$Qv = 12.78 \times 1.2 \times 1{,}005 \times 8$

$Qv = 123{,}301.44$ Watts

Where:

Qv (heat load)

V (airflow rate per second)

ρ (air density)

Cp (heat capacity)

Rearranging the formula (isolating variable ΔT)

$\Delta T = Qv / (V \times \rho \times Cp)$

$\Delta T = 123{,}301.44 / (12.78 \times 1.2 \times 1{,}005)$

$\Delta T = 123{,}301.44 / 15{,}412.68$

$\Delta T = 8°C$

The resulting air temperature drop is 8°C, based on the ISO range of 20–28°C. The final result is 20°C, with a heat rejection capacity of approximately 123,301.44 Watts.

Table 8. Air Temperature Comparison

Parameter	Existing	Alternative I	Alternative II	Alternative III
Average temperature (°C)	30,13	20	20	20
Heat dissipation (Watts)	0			
Compliance with standards	Does not yet meet	Approaching	Nearly meets	Meets upper limit
Temperature reduction capability	Low	Fair	Good	Very good

Based on ISO 17772-1, which specifies that the optimal temperature range for warehouses is 22–28°C, the temperature categories are as follows:

Table 9. Air temperature categories

Temperature Range	Category
22–28°C	Meets standards
>28–29°C	Nearly meets
>29–30°C	Partially meets
>30°C	Does not yet meet

The average temperature of 30.13°C exceeded the 22–28°C range established by the ISO 17772-1 standard, indicating that natural ventilation was not yet optimal for heat removal. The addition of ventilators increased heat removal capacity to 61,650.72 W for Alternative I, 92,427.84 W for Alternative II, and 123,301.44 W for Alternative III. Alternative III offered the best heat removal capacity and cooling performance. Roof ventilation also helped improve thermal comfort by regulating temperature, humidity, and air circulation. (Rusmiatmoko et al., 2018).

Humidity Analysis

An evaluation of relative humidity alternatives was conducted to determine the ventilation system's ability to reduce the accumulation of humid air within the warehouse, thereby maintaining product storage quality. (Rinanda et al., 2021).

Actual warehouse conditions

Calculate volumetric airflow rate (Q)

9,905.68 m³/h

Calculate air mass flow rate (m)

Air density at an average temperature of 30.13°C = 1.164 kg/m³

$m = Q \times \rho$

$m = 9{,}905.68 \times 1.164 = 11{,}530.21$ kg/h

Determine air humidity value

Based on the average warehouse air temperature of 30.13°C and average humidity of 77% compared to the ISO 17772-1 recommended range of 50–70% the water content value is:

X_initial (77%) = 20.88 g/kg

Calculate water load (W)

At 77% condition

Water content at 77% = 20.88

Water removal formula

$W = (26{,}785.22 \times 20.88) / 1{,}000$

$W = 559{,}275.39 / 1{,}000$

= 559.27 liters/hour

Actual conditions show an airflow rate of 9,905.68 m³/h and a mass flow rate of 11,530.21 kg/h. At a temperature of 30.13°C and a relative humidity (RH) of 77%, the water vapor content reaches 20.88 g/kg, exceeding the 50–70% RH range recommended by ISO 17772-1. This indicates high humidity levels, necessitating increased ventilation to reduce the accumulation of water vapor in the air.

Alternative Turbine I

Calculating volumetric airflow rate (Q)
23,011.36 m³/h
Calculating air mass flow rate (m)
Air density at an average temperature of 30.13°C = 1.164 kg/m³
m = Q x ρ
ṁ = 23,011.36 x 1.164 = 26,785.22 kg/h
Determining air humidity value
Based on the average warehouse air temperature of 30.13°C and average humidity of 77%—and noting that ISO 17772-1 specifies a humidity range of 50–70%—the moisture content values are:
X_initial (77%) = 20.88 g/kg
X_final1 (target 60%) = 16.15 g/kg
X_final2 (target 50%) = 13.40 g/kg
Calculating moisture removal load (W)
At 60% condition
Moisture content difference (77% - 60%) = 20.88 – 16.15
= 4.73 g/kg
Moisture removal formula
W = (26,785.22 x 4.73) / 1,000
W = 126,694.09 / 1,000
= 126.69 L/h
At 50% condition, moisture content difference (77% - 50%) = 20.88 – 13.40
= 7.48 g/kg
Moisture removal formula
W = (26,785.22 x 7.48) / 1,000
W = 200,351.8 / 1,000
= 200.35 L/h liters/hour

Alternative I increases the ventilation capacity to 23,011.36 m³/h with an air mass flow rate of 26,785.22 kg/h. The moisture removal capacity reaches 126.69 L/h at a target RH of 60% and 200.35 L/h at an RH of 50%,

Alternative Turbin II

Calculating volumetric air flow rate (Q)
34,517.04 m³/hour
calculate air mass flow rate (m)
Air density at an average temperature of 30.13C = 1.164 kg/m3
m = Q x ρ
ṁ = 34,517.04 x 1.164 = 40,177.83 kg/m3
determine the value of air humidity
based on the results the average air temperature in the warehouse is 30.13 C and the average air humidity value is 77%, based on ISO 17772-1 the air humidity value ranges from 50 – 70%, so the water content value is =
Xawal (77%) = 20.88 grams/kg
Xakhir1 (target 60%) = 16.15 grams/kg
Xakhir2(target 50%) = 13.40 grams/kg
calculate water load (W)
at 60% condition
difference in water content 77% - 60% = 20.88 – 16.15
= 4.73 grams/kg
water discharge can be calculated:
W=(40,177.83 x 4.73)/1,000
W=190,041.13/1,000
= 190.04 liters/hour
at 50% condition
difference in water content 77% - 50% = 20.88 – 13.40
= 7.48 grams/kg
Water disposal formula
W=(40,177.83 x 7.48)/1,000
W=300,530.16/1,000
= 300.53 liters/hour

Alternative II increases the air flow rate to 34,517.04 m³/hour, with a mass flow rate of 40,177.83 kg/hour. The moisture removal capacity reaches 190.04 L/hour at target RH 60% and 300.53 L/hour at RH 50%.

Alternative Turbine III

Calculating volumetric airflow rate (Q) = 46,022.72 m³/h
Calculating air mass flow rate (m)
Air density at an average temperature of 30.13°C = 1.164 kg/m³
m = Q x ρ
ṁ = 46,022.72 m³/h x 1.164 = 53,570.44 kg/h
Determining air humidity values
Based on the average warehouse air temperature of 30.13°C and average humidity of 77%—and noting that ISO 17772-1 specifies a humidity range of 50–70%—the moisture content values are:
$X_{initial}$ (77%) = 20.88 g/kg
X_{final1} (target 60%) = 16.15 g/kg
X_{final2} (target 50%) = 13.40 g/kg
Calculating moisture removal load (W) At 60% condition
Moisture content difference:
77% - 60% = 20.88 – 16.15 = 4.73 g/kg
Moisture removal formula
W = (53,570.44 x 4.73) / 1,000
W = 253,388.18 / 1,000 = 253.38 L/h
At 50% condition, moisture content difference:
77% - 50% = 20.88 – 13.40 = 7.48 g/kg
Moisture removal formula
W = (53,570.44 x 7.48) / 1,000
W = 400,706.89 / 1,000 = 400.70 L/h

Alternative III has the highest ventilation capacity at 46,022.72 m³/h, with a mass flow rate of 53,570.44 kg/h. Its moisture removal capacity reaches 253.38 L/h at 60% RH and 400.70 L/h at 50% RH.

Table 9. Comparison of Relative Humidity

Parameter	Eksisting	Alt I	Alt II	Alt III
Airflow rate (m³/h)	9.905,68	23.011,36	34.517,04	46.022,72
Air mass flow rate (kg/h)	11.530,21	26.785,22	40.177,83	53.570,44
Predicted RH after	77	73–75	70–73	68–71

ventilation (%)				
Moisture removal capacity to reach 60% RH (L/h)	-	126,69	190,04	253,38
Moisture removal capacity to reach 50% RH (L/h)	-	200,35	300,53	400,7
Compliance with ISO 17772-1 (50–70% RH)	Does not yet meet	Approaching	Nearly meets	Meets
Dehumidification capability	Low	Fair	Good	Very good

Based on ISO 17772-1, which specifies that the optimal humidity level for a warehouse ranges from 68% to 71% (RH), the humidity categories are as follows:

Table 10. Air Humidity Ranges

Air humidity (%RH)	Category
30–70% RH	Meets standards
>70–73% RH	Nearly meets
>73–75% RH	Partially meets
>75% RH	Does not meet

Current conditions show an airflow rate of 9,905.68 m³/h, a temperature of 30.13°C, and a relative humidity (RH) of 77%, exceeding the ISO 17772-1 recommendation (50–70%). Alternatives I, II, and III increase ventilation capacity to 23,011.36, 34,517.04, and 46,022.72 m³/h, respectively. Alternative II was selected as it offers a balance between air exchange, humidity control, the number of ventilators, and cost-efficiency.

Air Distribution

An evaluation of airflow distribution was conducted to assess the ability of each alternative to achieve uniform air dispersion. A more uniform distribution can reduce the formation of dead zones and prevent the accumulation of heat and moisture within the warehouse (Sahabuddin Latif, 2020).

Table 11. Comparison of Airflow Distribution

Parameter	Existing	Alternative I	Alternative II	Alternative III
Ventilator distribution	None	4 units	6 units	8 units
Air distribution pattern	Uneven	Fairly even	Even	Very even
Potential for stagnant zones	High	Moderate	Low	Very low
Airflow uniformity capability	Low	Fair	Good	Very good

Table 12. Airflow distribution categories

Level of Distribution	Category
The entire warehouse area receives even airflow.	Very good
Most areas receive airflow.	Good
There are still several areas with low air flow	Enough
Many areas with stagnant airflow.	Low

Current conditions indicate uneven air distribution, which potentially creates dead zones and leads to the accumulation of heat and moisture. Alternative II offers more uniform distribution, whereas Alternative III provides the most extensive circulation coverage. The number and placement of ventilators influence airflow patterns and the level of uniformity (Saputra & Arsianti, 2021).

Proper ventilation placement can also improve air uniformity and reduce zones with low circulation (Sandyawan & Putra, 2019). Based on air distribution parameters, Alternative III provides the most extensive circulation coverage and is the most effective at minimizing stagnant air zones.

Heat Reduction Effectiveness

The effectiveness of heat reduction is measured based on the increase in Air Changes per Hour (ACH) and the ventilator's ability to lower the warehouse temperature. The more effectively hot air is exhausted through the roof, the more optimal the temperature conditions and stability within the warehouse become (Noldy Tumembow & Siwi, 2021).

Table 13. Ventilation system parameters for reducing heat accumulation

Parameter	Eksisting	Alt I	Alt II	Alt III
ACH (times/hour)	0,37	1,02	1,34	1,66
Temperature (°C)	30,13	29–30	28–29	27–28
Heat dissipation capability	Low	Enough	Good	Very good

Table 14. Categories of heat reduction effectiveness levels

Air temperature	Condition	Effectiveness
>30°C	Above the recommended limit	Low
>29–30°C	Approaching the limit	Enough
>28–29°C	Almost meets the recommendations	Good
22–28°C	Meets ISO 17772-1 recommendations	Sangat Baik

Heat reduction effectiveness was evaluated based on Air Changes per Hour (ACH) and temperature, using a reference range of 22–28°C. Existing conditions showed an ACH of 0.37 h^{-1} and a temperature of 30.13°C, whereas Alternatives I, II, and III achieved ACH values of 2.32, 3.48, and 4.64, respectively, with corresponding temperatures of 29–30°C, 28–29°C, and 27–28°C. Alternative III yielded the best heat reduction results, as higher ACH values enhance heat dissipation and thermal stability (Syafira et al., 2022). However, based on the Performance-Based Design (PBD) approach, Alternative II was selected as it offers the

optimal balance between performance, air distribution, humidity, the number of units, and efficiency.

The selection of the alternative was based on a Performance-Based Design (PBD) approach, taking into account ACH values, ventilator distribution, air exchange capability, and unit quantity efficiency.

Table 15. Evaluation of Design Alternatives

Parameter	Alternative I	Alternatifve II	Alternative III
Number of ventilators	12 unit	19 unit	25 unit
ACH	2,32	3,48	4,64
ACH Compliance	meets	Meets requirements	Exceeds the limit
Ventilator distribution	Adequate	Good	Very good
Unit quantity efficiency	Good	Adequate	Low
Evaluation results	Adequate	Optimal	Exceeds the limit

(Source: Analysis and evaluation of research data)

Alternative I utilizes the fewest units, whereas Alternative III yields the highest ACH 4.64 air changes per hour but exceeds the 2–4 ACH target and requires the greatest number of units.

Alternative II achieves 3.48 ACH using 19 units, thereby striking a balance between air exchange capacity, distribution uniformity, and efficiency. Consequently, Alternative II was selected as the optimal design.

5. CONCLUSION

Based on the Air Change per Hour (ACH) analysis, the number of turbine ventilators required is 12 units for 2 ACH, 19 units for 3 ACH, and 25 units for 4 ACH. Current conditions show an ACH value of 0.37 air changes per hour and an average airflow velocity of 0.089 m/s, indicating that air circulation is suboptimal. By applying a Performance-Based Design (PBD) approach, Alternative II utilizing 19 units to achieve the 3 ACH target was selected because it offers a balance between air circulation, distribution uniformity, temperature and humidity control, and implementation efficiency.

Based on the design results, the turbine ventilators are positioned evenly across the warehouse roof surface to enhance airflow effectiveness and uniformity. Among the various alternatives developed, the configuration comprising 19 ventilator units was selected as the most suitable solution to improve air circulation within the food logistics warehouse.

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