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A Model on Energy Power Management of Air-Recirculation in a Clean Room

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ABSTRACT

With the rapid development of intelligent networking technology, fan filter units (FFUs) in cleanrooms can be networked as a cluster to form multiple low-pollution minienvironments. Therefore, FFU cluster management for different process cleanliness requirements and energy savings targets is a critical topic. This study uses particle swarm optimization with a metaheuristics algorithm to collect, calculate, and dynamically adjust air recirculation at a production site and plan FFU clusters for a cleanroom by integrating the FFU number, airflow speed, size, and other characteristics to ensure the quality of production and achieve energy savings targets.

Keywords: Minienvironment, clean room, fan filter clusters, cleanliness, energy savings, particle swarm optimization (PSO), metaheuristics algorithm.

INTRODUCTION

Background

Clean rooms are built for products that have processes with cleanliness requirements to ensure that these products are not contaminated by dust, dust particles, microorganisms, chemical volatiles, or erosion. Clean rooms are frequently used for advanced processes. Minienvironments are closed, isolated spaces with different levels of cleanliness for different products and processes. Construction of minienvironments is required because of the rapid development of the production of high-tech and special products. Processes are categorized on the basis of their cleanliness requirements by using the International Organization for Standardization (ISO 14644, 2015). Manufacturers create air recirculation systems with fan filter unit (FFU) clusters in cleanrooms by using product and process cleanliness specifications to ensure that dust particle and volatile chemical levels do not exceed environmental cleanliness limits. In cleanroom spatial planning, key air recirculation systems can be constructed with FFU clusters (Xu, 2005) in an intelligent network to create minienvironment air systems corresponding to the requirements for each space.

Research Motivation

The main function of FFU clusters in cleanrooms is to perform clean air recirculation and ensure product and process cleanliness. In cleanroom design, a sufficient number of FFUs (Xu et al., 2007) is required to filter clean air through wind speed adjustment to produce sufficient airflow volume in the dust-free space and control the cleanliness and particle concentrations. The cleanroom and minienvironment spaces must be provided by the air recirculation system with a sufficient air supply, air ventilation rate, wind speed, and power efficiency. Air recirculation systems are used to maintain cleanliness, and FFUs have substantial energy consumption.

High-tech and semiconductor companies have zero carbon emissions energy efficiency goals. Academic and industrial research is committed to ensuring high-quality products, high process yield rates, and reduced cleanroom energy consumption. However, the current high-tech industry has designed clean rooms and minienvironments by customizing FFU clusters for specific products and processes. If requirements change, readjusting facilities for energy savings is difficult.

The equipment required to divide a clean room into minienvironments is an FFU cluster; these clusters require a significant proportion of the overall cleanroom energy consumption (Xu, 2008). To meet air cleanliness specifications, the number and the configuration of FFUs in a divided space often exceeds the cleanliness requirements to ensure a sufficient cleanliness level throughout the cleanroom (Xu, 2007). Therefore, the number of FFU clusters is increased to increase air recirculation and achieve a sufficient safety margin. Thus, FFUs in a cleanroom often operate at a higher cleanliness level than necessary to achieve these margins and to facilitate repurposing of a clean room for new processes with higher cleanliness requirements, resulting in energy efficiency.

The research motivation is as follows:
1. To use intelligent networking technology to adjust cleanroom FFUs and divide them into minienvironments with different cleanliness levels and
2. To resolve the problem of excessive energy consumption due to high cleanliness requirements by adjusting FFU cluster operation to increase energy efficiency.

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Research Purpose
This research focuses on the energy efficiency management of FFU clusters in divided and undivided minienvironment spaces in a cleanroom to verify the cleanliness of the cleanroom through experiments and analysis of quantitative data. The number of FFUs clusters is configured in each divided space to optimize the energy efficiency information used by a controlling intelligent network. Energy efficiency management problems can be due to changes in product or process cleanliness requirements; energy efficiency management targets could be met by using intelligent networking technology. Experimental verification was performed using the FFUs’ energy power sensor module to obtain feedback and adjust the cluster to increase energy efficiency. The minienvironment can be adjusted to approximate the maximally efficient energy operation in a cleanroom by using this research model.

This research purpose is:
1. To develop a model for energy-efficient use of FFU clusters in a cleanroom.
2. To use a particle swarm optimization (PSO) model to increase the energy efficiency of FFUs and reduce the energy consumption of undivided cleanroom spaces.

LITERATURE REVIEW
On the basis of the key parameter data of cleanroom environmental control and operation, the required cleanliness in divided into cleanroom spaces, the energy-efficient operation model and minienvironment FFU cluster energy efficiency were evaluated, and a metaheuristic algorithm with quantitative data analysis was used to model clean room minienvironments and determine how to increase energy efficiency (Xu, 2005).

Cleanroom minienvironments have fixed divided spaces and FFUs. A metaheuristic algorithm with cluster intelligence characteristics was used to determine the problem validity, and multiple feasible solutions were applied in an FFU cluster to identify an optimal solution. This paper discusses quantitative studies of particle cluster optimization algorithms, the basic characteristics of the clusters applicable to this research model, and the use of internet of things (IoT) technologies to collect the basic parameters of FFUs. Feedback, control, and adjustments were implemented in the model to facilitate clean room FFU adjustment.

Control and Operation of Clean Room
The ISO-14644 2015 classes of air cleanliness by particle concentration were used to classify cleanroom cleanliness for control and operation.

Minienvironment (FFU Cluster) Design and Operation
The cleanroom divides minienvironments (differential segmented cleanliness levels for production processes) by using FFU clusters to protect products sensitive to contaminants by creating isolated, enclosed spaces in existing production sites. Minienvironment operations primarily consist of implementing FFU clusters in air recirculation systems to provide a sufficient clean airflow rate and effectively control pollutant concentrations.

Clean Room Classification
The ISO Classes of Air Cleanliness by Particle Concentration Guidelines include clean room and minienvironment air cleanliness classifications for specific industrial product implements or material requirement levels (ISO 14644-1, 2015).

FFU Cluster Energy Efficiency in Minienvironments
FFUs recirculate air to provide sufficient clean airflow volume and maintain cleanliness. Their main functions are air recirculation, energy adjustment, and control of dust particles in clean rooms.

FFU clusters can be easily installed above the ceiling of a minienvironment, and effectively managing energy consumption results in considerable energy savings in a minienvironment compared with that in a clean room (Xu, 2007).

Evaluating Minienvironmental Energy Efficiency Performance
The energy efficiency performance was evaluated in terms of airflow volume, airflow speed adjustment, and total power (watts) to determine the total energy consumption of the minienvironment. The less power is required per unit time, the higher the energy efficiency is. The energy efficiency performance indicator formula is power or airflow volume per unit of time \[\text{EPI} = \frac{W}{(m^3/min)}\] (Xu, 2006).

Key Energy Efficiency Parameters of FFUs with Intelligent Networking Technology
Air recirculation systems can be networked with wires or wirelessly. Sensors in the FFUs can monitor minienvironment energy consumption for a feedback control system; FFU speed can then be modified to approximate optimal operating parameters to provide sufficient clean air, control airflow speed, and optimize consumption efficiency by using repeated real-time data collection and feedback control. The FFU achieves approximately maximally efficient operation for a certain revolution per minute (RPM) requirement by using data such as airflow speed, energy consumption (W), airflow volume (Q), and efficiency.
FFU speed adjustment in the laboratory is used to produce energy efficiency data from the laboratory for implementation in minienvironment operations (Chen et al., 2007).

Key parameter information, such as RPM, airflow volume (m³/min), airflow speed, power consumption (W), and efficiency (η) are associated with product and process requirements to adjust the value of the reference energy efficiency requirement, approximate effective energy efficiency, and quickly and flexibly adjust the FFUs’ operation. Power consumption is defined as follows:

\[
\text{Power (W)} = \text{Total Pressure Difference (ΔP)} \times \text{Airflow Volume (Q)/Efficiency (η)}. \tag{1}
\]

Therefore, if the total value of the pressure difference (ΔP) can be maintained within a certain range of energy efficiency, the key parameter of an FFU is its airflow volume.

This study collected the key parameters for FFU energy efficiency. To reduce signal interference, mesh wireless IoT sensors were used to collect data, provide feedback, and control the FFUs. Moreover, an integrated wired (Wire RS485) energy efficiency control module was embedded in the FFUs to experimentally collect minienvironment field data and records of power efficiency to control the air recirculation system and adjust the FFU speed, airflow speed, and airflow volume. These data were collected for the target function value by approximating efficient energy consumption under the requirement of controlling the particle concentration (as the target value). The power density (W/m²) was used to adjust the airflow rate at a constant pressure difference (Pa). After the key energy efficiency parameters were collected, the operation of the air recirculation system of the controlled FFUs was adjusted in accordance with these parameters. The best solution identified by the algorithm was used to adjust the fan RPM, airflow speed in (m/s), and airflow volume (Qflow, Q/min) to achieve maximal energy efficiency.

**Metaheuristic Algorithm**

The metaheuristic algorithm produces too many feasible solutions in a short period; thus, identifying the best solution quickly is difficult. An algorithm was developed to approximate the best solution at a reasonable cost; however, it does not guarantee the optimal solution. An iterative algorithm evolution program was used to increase the learning efficiency by guiding generations of solutions, exploring development solutions, using learning strategies with structural information, classifying metaheuristic algorithms (Zahra et al., 2013), and solving for the approximate best solution of a cluster by using an iterative algorithm. In this study, a metaheuristic algorithm and PSO algorithm (Kennedy & Eberhart, 1995) were the most suitable for achieving a near-optimal solution for multiple clusters.

**RESEARCH METHOD**

**PSO**

The PSO algorithm was applied to FFU clusters because it is effective for finding the most feasible solutions in a cluster in situations where an optimal solution cannot be found immediately. The speed adjustment value is calculated through iterative memory and finally reaches the approximately optimal position when approaching a foraging direction path. The particle cluster optimization algorithm was adopted. The algorithm applies to all clusters and finds the most feasible solutions but requires substantial time. Iterable evolution is first solved and finally converges to an approximately optimal solution.

The PSO calculation stages are as follows (Kennedy & Eberhart, 1995):

1. Initial feasible solution.
2. Calculating the target value (fitness function).
3. Correction:
   
   **Correction 1:** Comparing best feasible solution position value \(p_{best}(t,d)\) of the flock of birds (particles).
   
   **Correction 2:** Comparing best feasible solution position value \(g_{best}(t,d)\) of all the birds (particles).

4. Calculating the speed adjustment value by using (1).
   
   \[
   V_i(t+1) = wV_i(t) + c_1r_1[p_{best} - X_i(t)] + c_2r_2[g_{best} - X_i(t)] \tag{1}
   \]

5. Next-generation particle position: this generation’s particle position + next generation’s particle velocity vector adjustment from (2).
   
   \[
   X_i(t+1) = X_i(t) + V_i(t+1) \tag{2}
   \]

6. They are iteratively calculating the corresponding value of the next-generation feasible solution to optimize the objective function.

7. Halting rules:

   **Rule 1:** Performing \(n\) generations (\(n\) is the confirmation generation number).
Rule 2: Improvement below a fixed threshold (insufficiency affects the number).

Model for FFU Cluster (Air Recirculation) Energy Efficiency Management

Energy efficiency parameters of FFU clusters were first identified, and the PSO algorithm was then applied to achieve optimal energy management.

The model parameters (Figure 1) and calculation steps are as follows:

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>Particles/m³, Particle Cleanliness</td>
</tr>
<tr>
<td>PN/s</td>
<td>Particle Number/Second, Particle Number</td>
</tr>
<tr>
<td>AVR</td>
<td>Air Velocity Rate (Airflow Volume)</td>
</tr>
<tr>
<td>it</td>
<td>Iteration</td>
</tr>
<tr>
<td>Sij</td>
<td>Product i, Process j, Air Speed in minienvironment (m/sec)</td>
</tr>
<tr>
<td>Nij</td>
<td>Product i, Process j, Fan Filter Units in minienvironment (m/sec)</td>
</tr>
<tr>
<td>Pa</td>
<td>Product i all process</td>
</tr>
<tr>
<td>PLbest,i</td>
<td>Particle (Feasible) Local Best search in own minienvironment</td>
</tr>
<tr>
<td>PGbest,i</td>
<td>Particle (Feasible) Global Best search in own minienvironment</td>
</tr>
<tr>
<td>Ci, C2</td>
<td>Learning Factor</td>
</tr>
<tr>
<td>r1, r2</td>
<td>Random Variable</td>
</tr>
<tr>
<td>W</td>
<td>Inertia Weight</td>
</tr>
<tr>
<td>Uij</td>
<td>Low Bound</td>
</tr>
<tr>
<td>Uij</td>
<td>Upper Bound</td>
</tr>
<tr>
<td>TEC</td>
<td>Total Energy Consumption</td>
</tr>
<tr>
<td>EI</td>
<td>Energy Performance Index</td>
</tr>
<tr>
<td>EPD</td>
<td>Electronic Power Density</td>
</tr>
</tbody>
</table>

**Source:** This study.

Figure 1: Parameters of FFU clusters.

1. The feasible solution: FFU clusters in each divided space (multiple combinations of different FFU clusters in different processes).
2. Decision variable: the number of FFUs clusters in the minienvironment space.
3. Adjusted value: airflow speed.
4. Target value of fitness function: energy efficiency (total energy consumption [TEC]).
5. The number of FFU clusters in the next generation = the current number of FFU clusters + the next-generation adjustment value.

\[ N_{ij}(it + 1) = N_{ij}(it) + S_{ij}(it + 1) \]  \hspace{1cm} (2)

6. Next-generation airflow speed adjusted value = current airflow speed + the best value for the FFU clusters.

\[ S_{ij}(it + 1) = S_{ij}(it) + C_1 r_1 \times (PL_{best,i}(it) − N_{ij}(it)) + C_2 r_2 \times (PG_{best}(it) − N_{ij}(it)) \]  \hspace{1cm} (3)

7. Halting condition: TEC improves less than the influence value.

By using the decision variable of the minienvironment in cleanroom (FFU clusters), the airflow speed was adjusted to meet the target function minimizing TEC. A feasible solution for the minienvironment was generated and compared with the solution cluster to identify the optimal target value for energy consumption. The correction was performed to obtain the next generation of feasible solutions. After repeated calculation adjustments, a solution approximating the optimal minienvironment can be obtained. The target function for the approximately optimized energy-efficient solution was identified on the basis of the target cleanliness level.

The PSO algorithm was used to optimally operate an FFU air recirculation system. The key parameters for cleanliness and energy efficiency are as follows:
1. Particle cleanliness (PC): number of particles per cubic meter that are dust particles (particles per m³).
2. Particle number (PN/s): particles per second produced in the cleanroom.
3. Number of FFUs.
4. Cleanroom pressure value (Pa): the pressure in the cleanroom.
5. Air velocity rate (AVR): air produced per second in cubic meters (m\(^3\)/s).
6. High-efficiency particulate air filter area (HEPA, A): square meters covered by HEPA (m\(^2\))
7. Airflow speed (S): airflow in meters per second (m/s).
8. TEC: total energy consumption of the cleanroom.

\[
P_C = \frac{PN/s}{AVR} \tag{4}
\]

\[
AVR = S \times A \tag{5}
\]

\[
P_C = \frac{PN/s}{AVR} = \frac{PN/s}{(S \times A)} \tag{6}
\]

\[
S = \frac{PN/s}{(PC \times A)} \tag{7}
\]

\[
S_j = \frac{PNj/s}{(PC_j \times A \times nj)} \tag{8}
\]

In process j, the airflow speed is S\(_j\), the particle number is PN\(_j/s\), the particle cleanliness is PC\(_j\), and the number of FFUs is nj.

**EXPERIMENTAL DESIGN AND RESULTS**

**Parameters of FFUs in Energy Efficiency Management Model**

Key parameters of FFUs were collected using intelligent networking technology in the minienvironment (Figure 2 and Table 1).

1. AVR = airflow speed (S) \times high-efficiency filter area (A), formula: AVR = S \times A
2. Airflow speed: velocity measured using test equipment corresponding to the airflow speed of the FFUs in Figure 2.
3. EC: power consumption measured using sensors corresponding to the power consumption of the FFUs.

![Power Transducer](image1)

![Airspeed Meter](image2)

![Air Sensor](image3)

**Source:** This study.

Figure 2: Experimental design for FFU cluster parameters.

<table>
<thead>
<tr>
<th>FFU RPM</th>
<th>600</th>
<th>850</th>
<th>700</th>
<th>750</th>
<th>800</th>
<th>900</th>
<th>1000</th>
<th>1050</th>
<th>1100</th>
<th>1150</th>
<th>1200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Power (W)</td>
<td>22.9</td>
<td>27.2</td>
<td>32.7</td>
<td>40.7</td>
<td>48.5</td>
<td>57.5</td>
<td>67.9</td>
<td>79.5</td>
<td>92.4</td>
<td>107.7</td>
<td>123.9</td>
</tr>
<tr>
<td>Airflow Speed (M/S)</td>
<td>0.24</td>
<td>0.26</td>
<td>0.34</td>
<td>0.36</td>
<td>0.42</td>
<td>0.45</td>
<td>0.45</td>
<td>0.57</td>
<td>0.59</td>
<td>0.68</td>
<td>0.78</td>
</tr>
<tr>
<td>Airflow Volume (cfm)</td>
<td>581.9</td>
<td>632.5</td>
<td>736.5</td>
<td>798.9</td>
<td>922.4</td>
<td>983.3</td>
<td>996.6</td>
<td>1029</td>
<td>1304</td>
<td>1561</td>
<td>1581</td>
</tr>
<tr>
<td>Airflow Rate through the Cleanroom minienvironment (Btu/Ad air per Hour)</td>
<td>0.01</td>
<td>0.043</td>
<td>0.446</td>
<td>0.651</td>
<td>0.602</td>
<td>0.608</td>
<td>0.606</td>
<td>0.604</td>
<td>0.607</td>
<td>0.601</td>
<td>0.605</td>
</tr>
</tbody>
</table>

**Source:** This study.

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MODEL VALIDATION

Experimental Situation

Experimental site and facility conditions
Production of a mobile phone camera module in a cleanroom.
1. Manufacturing process:
   (1) Cell phone lens sensor chip packaging.
   (2) Optical focus correction.
   (3) Lens optical module assembly.
2. Minienvironment classification of cleanliness (different working spaces, different cleanliness classes, three minienvironments).
   (1) Cleanliness level 5 for the first minienvironment.
   (2) Cleanliness level 5 for the second minienvironment.
   (3) Cleanliness level 6 for the third minienvironment.
3. Using FFU clusters with the energy efficiency management model to reduce power consumption.
4. Cleanroom space: 18 m (width) × 30 m (length) × 2.5 m (height), area (square meters): 540 m², space (cubic meters): 1,350 m³.
5. FFUs are equally distributed in the cleanroom.
6. All FFUs must be running (otherwise, pollutants will enter).
7. The airflow speed is the same as that in the minienvironment.
8. Number of FFUs: 100 units, three different processes, 100 units/540 m², 1 unit = 5.4 m²
9. FFU specifications: 0.57 m (width) × 1.1 m (length) × 0.25 m (height).
10. HEPA: nondamaged, unclogged.
12. Objective function: TEC.

Energy efficiency management model of PSO algorithm

\[ n_{ij}(t+1) = n_{ij}(t) + s_{ij}(t) \]  
\[ s_{ij}(t) = Ws_{ij}(t) + C_1 r_1 (P_{Lbest} - n_{ij}(t)) + C_2 r_2 (P_{Gbest} - n_{ij}(t)) \]

1. \( n_{ij} \) = number of FFUs (calculated and adjusted by the algorithm).
2. \( s_{ij} \) = airflow speed (after calculating the airflow volume to check the parameters of FFUs in the energy efficiency management model).
3. \( W \): inertial weight, constant value (0.8 – 1.2).
4. \( C_1, C_2 \): learning factor \( C_1 = C_2 \in [1, 2.5] \), the usual value is 2.
5. \( r_1 \) and \( r_2 \) are random parameters in (0,1).
6. \( L_{ij} \) = minimum number of fans (given by process).
7. \( U_{ij} \) = maximum number of fans:

\[ U_{ij} = N - \sum_{k=1}^{j-1} L_{ik} \sum_{k=j+1}^{N} L_{ik} \]  

(Total number of fans: the sum of the least number of fans in the remaining space).

Results for calculated feasible solutions after the first generation of PSO (Table 2).

<table>
<thead>
<tr>
<th>Cleanliness Class S-6, First Generation, t=1, Particle Swarm Optimization Algorithm in Minienvironments</th>
<th>Airflow Volume ( \times ) number of FFUs, speed of all fans</th>
<th>Check Experimental Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Source:</strong> This study.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Calculated feasible solutions for the first generation of PSO.
Benchmarking Comparison
A power consumption evaluation was performed by comparing spaces with three types of cleanrooms.
1. Cleanroom undivided spaces (Table 3).
2. Cleanroom divided spaces, nonadjustable mini environments (Table 4).
3. Cleanroom divided spaces (this study), adjustable mini environments (Table 5).

Table 3: Power consumption in undivided cleanroom spaces.

<table>
<thead>
<tr>
<th>Fan Filter Limits</th>
<th>Feasible</th>
<th>Air Flow Rate 10 times (Class 5)</th>
<th>Check Experimental Parameters</th>
<th>Power (Watt)</th>
<th>Energy Efficiency (W/m³/min)</th>
<th>Electronic Power Density (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 FFUs</td>
<td>100</td>
<td>0.4156</td>
<td></td>
<td>5749</td>
<td>9.954</td>
<td>19.64</td>
</tr>
</tbody>
</table>

Source: This study.

Table 4: Power consumption in divided cleanroom spaces, nonadjustable mini environments.

<table>
<thead>
<tr>
<th>FFU Qty</th>
<th>Feasible</th>
<th>Air Flow Rate 10 times (Class 5)</th>
<th>Check Experimental Parameters</th>
<th>Power (Watt)</th>
<th>Energy Efficiency (W/m³/min)</th>
<th>Electronic Power Density (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>1.4456</td>
<td></td>
<td>4749.82</td>
<td>0.992</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Source: This study.

Table 5: Power consumption in divided cleanroom spaces, adjustable mini environments.

<table>
<thead>
<tr>
<th>FFU Qty</th>
<th>Feasible</th>
<th>Air Flow Rate 10 times (Class 5)</th>
<th>Check Experimental Parameters</th>
<th>Power (Watt)</th>
<th>Energy Efficiency (W/m³/min)</th>
<th>Electronic Power Density (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>0.4436</td>
<td></td>
<td>43.35</td>
<td>0.018</td>
<td>7.99</td>
</tr>
</tbody>
</table>

Source: This study.

CONCLUSION
The energy management model was verified through experiments, and the air recirculation system can be introduced to adjust the airflow volume and airflow speed of the FFU clusters. The PSO algorithm with the metaheuristic algorithm was used. The quantitative research data analysis revealed that energy efficiency could be increased. Cleanroom energy efficiency consultants and production plan designers could effectively split a cleanroom into minienvironments to reduce the TEC of the FFU clusters to increase energy efficiency, produce high-quality products, and flexibly adjust to changing requirements.

The paper achieves the following:
1. We are applying PSO to develop a model for energy-efficient FFU clusters in a cleanroom.
2. We are demonstrating the model’s ability to increase the energy efficiency of FFU clusters in a clean room on the basis of the experimental results.

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