1. Introduction

With the improvement in mine tunneling technology, the total dust concentration at
the working face is as large as 2500–3000 mg/m³, which seriously threatens the driver’s
health and safe production [1]. An air curtain dust control technology uses the plane
injection formed by the injection cavity (IC) installed at the forward roadheader to isolate
dust-containing gas at the working face away from the driver’s working area and achieve
the control of dust at the working face as much as possible [2], as shown in Figure 1. The air
curtain dust control system can be broadly divided into the fan system, pipeline system, IC
system and other auxiliary systems [3]. The design of each system should consider different
design indicators. The power, size and installation convenience should be considered for
the fan system. Airtightness and volume should be considered for the pipeline system. The
size, maintainability and replaceability should be considered for the IC system. Meanwhile, due to different production methods, tunnel conditions, using habits and other differences, various mines have different requirements for the air curtain dust control system. The installation tightness of an ACDCD with a roadheader affects the stable operation and dust control effect of the ACDCD. When the tunnel size does not match the ACDCD, the ending of the air curtain does not reach the top of the tunnel. The above problems restrict the industrialization process of the ACDCD and cannot meet the demand of large-scale application in the market today. The modular design (MD) can effectively solve these problems. The MD is an effective approach to reduce product manufacturing costs, shorten R & D cycles and solve multiple customized needs of users [4].

The MD is a systematic design method that combines complex product information with manufacturing rules. Product modularity can decompose complex products into simple component manufacturing tasks [5], thus, important components of the product are replaceable. MDs can improve the utilization of products without increasing the cost of time and create sustainable value [6]. Moreover, for large-scale customization, product modularity has a positive impact on product diversity [7]. In mass customization, modular components are standardized, and different functional modules are independently designed and manufactured without mutual influence [8,9]. Li et al. (2019) proposed a modular combined design method for the existing problems of mine rescue cabins. The effectiveness of modular combined life-saving cabin design was verified by simulated load analysis of the structural model [10]. Chen (2019) proposed a modular spray-proof dust removal device considering the shortcomings of the existing spray-proof dust removal device, such as complex installation and laborious handling and installation [11]. Aimed at the common drilling conditions and the construction needs of full-section penetrating drilling in coal mines, a series of penetrating drilling rigs with 300 M drilling depth construction ability were developed and designed by using a modular design method [12]. According to the actual situation of a coal mine, Hao et al. (2014) proposed a modular design of an underground drainage pump monitoring system [13]. The above researchers mainly applied MDs from three perspectives: coal mine equipment, coal mine construction technology and coal mine management, to achieve high-quality and efficient production in coal mines. However, according to our investigation, there has been no modular study of ACDCDs. Therefore, the idea of modularity is introduced into ACDCD design in this paper, thereby improving the replacement and maintenance of ACDCDs and reducing the maintenance cost and iterative design cost of ACDCDs.

Module division is an essential step in MD. Whether the module division is reasonable affects the product function, structure and cost. There are many standards for module division, and the most commonly method is functional division. Li et al. (2012) proposed a hybrid module decomposition method and successfully applied it to the division example of an elevator car [14]. Wang et al. (2018) proposed a modular design method based on fuzzy cluster module division for the problems of high input costs and low reutilization rates existing in current coal mine paste filling stations [15]. Li et al. (2013) proposed an integrated product modularization scheme based on flow analysis, design structure matrix

Figure 1. Schematic diagram of air curtain dust control system. 1, tunnel; 2, roadheader; 3, air curtain; 4, ACDCD; 5, driver; 6, air fan.

The rest of this paper is organized as follows. Section 2 introduces the MD and the IACDCD. Section 4 gives a case of ACDCD modularization, lists the final module division, and analyzes the existing SCA method considering the functional and structural correlation matrix of component data. Section 3 analyzes the effectiveness of modular combined life-saving cabin design was verified by simulated load analysis of the structural model [10]. Chen (2019) proposed a modular spray-proof dust removal device considering the shortcomings of the existing spray-proof dust removal device, such as complex installation and laborious handling and installation [11]. Aimed at the common drilling conditions and the construction needs of full-section penetrating drilling in coal mines, a series of penetrating drilling rigs with 300 M drilling depth construction ability were developed and designed by using a modular design method [12]. According to the actual situation of a coal mine, Hao et al. (2014) proposed a modular design of an underground drainage pump monitoring system [13]. The above researchers mainly applied MDs from three perspectives: coal mine equipment, coal mine construction technology and coal mine management, to achieve high-quality and efficient production in coal mines. However, according to our investigation, there has been no modular study of ACDCDs. Therefore, the idea of modularity is introduced into ACDCD design in this paper, thereby improving the replacement and maintenance of ACDCDs and reducing the maintenance cost and iterative design cost of ACDCDs.

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and fuzzy clustering. They developed an improved SMACOF method for converting two-dimensional space vectors, and then used the fuzzy C-means clustering method to divide modules to verify the effectiveness of the algorithm through the case analysis of the modularity of a hydraulic support platform [16]. The spectral clustering algorithm (SCA) is a clustering method based on a data similarity matrix, which is very effective for clustering sparse data. SCA is based on graph theory. Compared with traditional clustering algorithms, SCA has the advantages of non-convex sample space clustering and convergence to a global optimal solution in a relaxed continuous domain [17]. Liu et al. (2020) proposed an improved SCA for the cluster problem in the cognitive process of a vehicle cooperative environment, which effectively improved the stability of the cluster [18]. Sapkota et al. (2019) combined SCA with K-means and NFPH to propose an improved SCA [19]. The clustering error reduction of this method by 2% and the clustering accuracy were demonstrated by test datasets in the medical field. However, the mapping between the construction of the similarity matrix and the products is necessary to further strengthen when the existing SCA performs the clustering division. The SCA is extremely sensitive to the choice of similarity matrix.

Aimed at the above problems, we applied the SCA modularity method to the modularity study of the ACDCD. We proposed a modular method of the ACDCD based on improved spectral cluster algorithm (ISCA) module division and proposed an improved air curtain dust control device (IACDCD). Specifically, a similarity matrix construction method considering the functional and structural correlation matrix of components was proposed to strengthen the connection relationship of components. The two existing ACDCDs and the IACDCD were modularized using the improved spectral cluster module division method. The rest of this paper is organized as follows. Section 2 introduces the modular method of the ACDCD based on ISCA. Section 3 analyzes the existing ACDCDs and the IACDCD. Section 4 gives a case of ACDCD modularization, lists the final cluster results and relevant analysis. Finally, the concluding remarks are summarized in Section 5.

2. Methods

2.1. The Concept of Modular Design

Due to the growing resource needs and sustainable development needs, a design approach that considers the full life cycle technology of the product should be used to design it. The product life cycle here includes: green design, material selection, manufacturing and assembly, using and maintenance, disassembly and recovery. With the progress of technology and the development of industry, the needs of customers present diversified and personalized characteristics. The modularity can improve the versatility and interchangeability of common parts of the product and realize the diversification of the product with small changes satisfying the personalized needs of users. The MD of products is one of the important methods to solve above problems.

The MD divides the product into universal and special product modules according to the structure or function of the product. Li et al. (2018) realized large-scale, personalized, low-cost and rapid design through the combination of internal modules of physics and services facing the problem of modular design framework of large-scale personalized product service system [20]. Modules are defined as stand-alone units with specific interfaces and functions in childhood [21]. The universal module is a common module in the series of products, with uniform size and shape. The special modules are modules implementing specific functions and satisfying the needs of different using scenarios.

2.2. Quantification of Relevance of Product Function and Structure

There are two main factors affecting product division: function and structure. From a mechanical perspective, structural connections between parts can use welding, bonding, dovetail and riveting. Different attachment methods represent different degrees of tightness. In the existing product division method, the connection of two parts is determined by 0 and 1. The value 1 indicates that the parts are connected and 0 indicates that the parts
are independent. This division method cannot clearly represent the tightness of two parts. Moreover, there is also a lack of quantitative description on the product function.

Assuming that a product $A$ has $n$ parts. $\text{fun}_{i,j}$ represents the functional strength values of part $i$ and part $j$. The functional strength values are defined as shown in Table 1.

| Values | Description                          |
|--------|--------------------------------------|
| 8      | Cooperate to perform the same function |
| 6      | High degree of synergy                |
| 4      | Moderate degree of synergy            |
| 2      | Less synergy                          |
| 0      | No synergistic functional relationship |

$\text{str}_{i,j}$ represents the structural strength values of part $i$ and part $j$. The structural strength values are defined as shown in Table 2.

| Values | Description                                      |
|--------|--------------------------------------------------|
| 8      | Very strong connectivity                         |
| 6      | Connection relation                              |
| 4      | General Connection Relationship                   |
| 2      | Weak connection relation                         |
| 0      | No connection relationship                       |

$R_{i,j}$ represents the quantitative connection relation (QCR) between part $i$ and part $j$. $\alpha$ represents the value of product function weight. The larger the value, the more attention is paid to the functional connection of the product. Therefore, we obtain the QCR matrix of $N$ parts of product $A$. $\text{Link}_A$ represents the QCR matrix.

$$R_{i,j} = \alpha \text{fun}_{i,j} + (1 - \alpha) \text{str}_{i,j}$$

$$\text{Link}_A = \begin{bmatrix}
R_{1,1} & R_{1,2} & \cdots & R_{1,n} \\
R_{2,1} & R_{2,2} & \cdots & R_{2,n} \\
\vdots & \vdots & \ddots & \vdots \\
R_{n,1} & R_{n,2} & \cdots & R_{n,n}
\end{bmatrix}$$

2.3. **Modular Method Based on Improved Spectral Clustering Algorithm**

An SCA is a graph theory-based clustering method [22]. The purpose of clustering the sample is achieved by clustering the eigenvectors of the Laplacian matrix of the sample. A spectral clustering is a method of mapping data from a high-dimensional space to a low-dimensional space and clustering using other clustering algorithms in a low-dimensional space. SCA converts the data into an undirected weighted graph in space and clusters the data using the concept of spectrum in graph theory. We describe graph $G$ by the set $X$ of points and the set $E$ of edges, that is $G(V, E)$, where the $X$ is all points to be clustered. $X = \{x_1, x_2, \ldots, x_n\}$. There may or may not be a connection relationship for any two points in the $X$. Define the weight $\omega_{ij}$ as the connection weight between point $i$ and point $j$. Since the $G$ is an undirected graph, $\omega_{ij} = \omega_{ji}$. Using the weight values between all points, the affinity matrix $W$ of $X$ can be obtained. The standard SCA mainly includes the following six steps [23].

(1) Calculation of similarity matrix $S$. If we only have the definition of sample points and no weight value between sample points, $W$ cannot be obtained directly. Therefore, the similarity matrix $S$ was used to obtain $W$ indirectly. The basic idea is that the weight of two points far away is low and weight of two points close together is high. The similarity
matrix $S$ is generally calculated by Euclidean matrix or Gaussian kernel function, and the calculation expression is shown as follows

$$s_{ij} = \exp\left(-\frac{||x_i - x_j||^2}{2\sigma^2}\right)$$

(3)

$$S = \begin{bmatrix} s_{1,1} & \cdots & \cdots \\ \vdots & \ddots & \vdots \\ \cdots & \cdots & s_{n,n} \end{bmatrix}$$

(4)

where $x_i$ represents the $i$th sample points; $s_{ij}$ represents the distance between sample $i$ and sample $j$; $\sigma$ represents the scale parameters of RBF kernel; $S$ represents the similarity matrix.

(2) Calculation of affinity matrix $W$. According to the similarity matrix $S$, there are generally three methods to construct $W$: $\epsilon$ proximity method, $K$ proximity method and full connection method.

The $\epsilon$ proximity method. By setting the threshold, $W$ is constructed according to the relationship between $s_{ij}$ and $\epsilon$.

$$\omega_{ij} = \omega_{ji} = \begin{cases} 0, & s_{ij} > \epsilon \\ \epsilon, & s_{ij} \leq \epsilon \end{cases}$$

(5)

The $K$ proximity method. The $k$ sample points closest to sample point $i$ serve as nearest neighbor points. $K$ nearest neighbor points constitute the $K(x)$ sets. $W$ is constructed according to $s_{ij}$.

$$\omega_{ij} = \omega_{ji} = \begin{cases} 0, & x_i \notin K(x_j) \text{ and } x_j \notin K(x_i) \\ s_{ij}, & x_i \in K(x_j) \text{ or } x_j \in K(x_i) \end{cases}$$

(6)

The full connection method. The similarity matrix is regarded as an affinity matrix.

$$\omega_{ij} = \omega_{ji} = s_{ij}$$

(7)

$$W = \begin{bmatrix} \omega_{1,1} & \cdots & \cdots \\ \vdots & \ddots & \vdots \\ \cdots & \cdots & \omega_{n,n} \end{bmatrix}$$

(8)

(3) Calculation of degree matrix $D$ and Laplacian matrix $L$. The degree $d_i$ of sample point $i$ is the sum of the weights of all the edges connected. The degree matrix $D$ is obtained by calculating the point degree of each sample.

$$d_i = \sum_{j=1}^{n} \omega_{ij}$$

(9)

$$D = \begin{bmatrix} d_1 & \cdots & \cdots \\ \vdots & \ddots & \vdots \\ \cdots & \cdots & d_n \end{bmatrix}$$

(10)

The Laplacian matrix construction formula is shown below

$$L = D - W$$

(11)

(4) Calculation of eigenmatrix $F$ corresponding to the $k$ minimum eigenvalues of $D^{-1/2}LD^{-1/2}$. After obtaining the Laplacian matrix, the $G$ is cut by the tangent graph method, and the graph is divided into several independent subgraphs. There are three common cutting criteria: the minimum cut criterion, the proportional cut criterion, and the canonical cut criterion. The Laplacian matrix is solved after the secant criterion is determined. A common standardized Laplacian matrix solution method is used here.
$L_{sym}$ represents the normalized Laplacian matrix. The eigenvector $F$ corresponding to $k$ eigenvalues with minimum $L_{sym}$ is solved. Here, $k$ represents the clustering number.

$$L_{sym} = D^{-1/2}LD^{-1/2}$$  \hspace{1cm} (12)

(5) The $F$ was clustered using the K-means clustering algorithm.

(6) Output Clustering Results.

The SCA differ in the approach similarity matrix calculated and the approach Laplacian matrix represented. In the existing research of applying spectral clustering to module division, the weight between each part is defined as 0 or 1. A value of 1 indicates that the parts are connected and 0 indicates that the parts are independent. This similarity matrix calculation neglects the correlation between part function and structure. Due to the differences in structure and function of different parts, the relationship between parts cannot be accurately expressed using unified treatment. This affects final module division results. Therefore, an improved spectral clustering modularity method is proposed. Assuming that a product $A$ has $n$ parts, and considering the QCR matrix proposed by 2.2, we denote $Link_A$ as the initial connection relation matrix of the spectral cluster, i.e.,

$$S_{ij} = \exp\left(-\frac{||x_i - x_j||^2}{2\sigma^2}\right) = \exp\left(-\frac{||R_{ij}||^2}{2\sigma^2}\right)$$  \hspace{1cm} (13)

The above (2)–(6) calculation steps are used, and finally the proposed ISCA is obtained.

3. Analysis of Existing ACDCD and the IACDCD

3.1. Analysis of Existing ACDCD

Air is ejected from the IC of the ACDCD to the walls and the upward tunnel, forming a transparent air barrier, which separates the polluted area with a high concentration of dust from the driver work area, as shown in Figure 1. This air barrier prevents dust from spreading to the driver’s area, thereby ensuring the purity of the air breathed by the driver. Moreover, this barrier is transparent and does not have an impact on the driver’s vision. There are two main factors that affect the dust isolation effect of the air curtain: the ability of the air curtain to entrap the surrounding air, and the ability of the air curtain to resist diffusion. The stronger the air curtain’s ability to absorb the surrounding air, the larger the amount of dusty air is absorbed. The more the dustier air reaches the tunnel, the more dust will diffuse into the driver’s area. The ability of the air curtain to entrap the surrounding air and the ability of the air curtain to resist diffusion are mutually affected. Increasing the width of the IC and the outlet air speed can strengthen the anti-diffusion ability of the air curtain, but it will also increase the suction capacity of the air curtain. According to previous studies, the air curtain outlet velocity is generally in the range of 10 m/s–20 m/s, and the IC outlet width is generally in the range of 6 mm–20 mm [24].

Figure 2 shows the 3D schematic diagram of the ACDCD proposed by Yucheng Li (2010) [24]. The device used an inverted ‘U’ IC and a triangular injection box to form the main injection device. The triangular injection box not only had less resistance, but also could regulate the direction and the wind speed of the injection in multi-stages and multi-segments. The device was about 2.4 m long and 1 m high, and the diameter of the air duct was 260 mm. When the wind speed of the roadway wall jet was controlled at about 2 m/s, the device was suitable for comprehensive tunneling dust control with different sections. Through a laboratory test, industrial test and numerical simulation, this device could form an effective air curtain when the air speed at the jet outlet was between 10 m/s and 20 m/s, and the IC outlet width was between 6 mm and 20 mm. Figure 3 shows the 3D schematic diagram of the ACDCD proposed by Zongtao Liu (2019) [25]. The main injection device was composed of a simplified injection box, four independent ICs and a hose system. The injection box had one air inlet and four air outlets. Four separate ICs had vanes. The regulation of the outlet velocity of the air curtain injection was achieved by the outlet width, the vane and the air pressure. The device was about 2.6 m long and
According to previous studies, the air curtain outlet velocity is generally in the range of 35–779 m/s, costly iterative design and difficulty in the promotion. Zongtao Liu’s device simplified the injection box and a triangular injection box to form the air curtain outlet velocity, thus reducing the complexity of the ACDCD and improving the flexibility of the ACDCD. Moreover, the ‘U’ type injection cavity was customized with the disadvantages of a costly iterative design and the affect on the driver’s operation and inflexible movement. Moreover, the ‘U’ type injection cavity was customized with the disadvantages of a costly iterative design and difficulty in the promotion. Zongtao Liu’s device simplified the injection box and split the integrated inverted ‘U’ injection cavity into four independent injection cavities. Four separate injection cavities were connected by fixed brackets. However, Zongtao Liu’s device still had the drawbacks of a complex installation, costly maintenance and costly iterative design.

3.2. The Improved ACDCD

An improved ACDCD was proposed in this paper to adapt to more application scenarios, reduce the complexity of the ACDCD and improve the flexibility of the ACDCD, as shown in Figure 4. Compared with Zongtao Liu’s device, the injection box and the fixed bracket were removed. Moreover, the IC size and the pipeline system were unified. The 3D schematic diagram of the improved IC is shown in Figures 5 and 6. The injection box was mainly used to divide the inlet air average into four ICs. The inlet air of the four ICs should be as consistent as possible to ensure the injection of the IC meets the conditions for forming the air curtain. We unified the size of the IC. Therefore, only the air distribution tube could satisfy the air distribution requirements. The angle of the individual ICs was adjusted by a bolt that connected the IC to the fixed bracket, as shown in Figure 5. We placed isokinetic wedges in each IC to ensure that the outlet air was isokinetic.
4. Case Analysis

4.1. Quantification of Relevance of Different ACDCD

The module division of the ACDCD was carried out using the improved spectral clustering modularization method, and the QCR was carried out first. The 3D diagrams of Yucheng Li’s ACDCD, Zongtao Liu’s ACDCD and the IACDCD were drawn by CATIA software. The 3D explosion diagrams were made, which are shown in Figures 7–9, respectively.
Figure 6. The improved injection cavity. 6, constant wedge.

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4.1. Quantification of Relevance of Different ACDCD

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Figure 7. A 3D exploded diagram of ACDCD proposed by Yucheng Li.

| Number | Description          |
|--------|----------------------|
| P1     | Air fan              |
| P2     | No.1 Air duct        |
| P3     | No.2 Air duct        |
| P4     | No.1 Injection box   |
| P5     | No.2 Injection box   |
| P6     | The right IC         |
| P7     | The upper IC         |
| P8     | The left IC          |

Figure 8. A 3D exploded diagram of ACDCD proposed by Zongtao Liu.

In the case of Li Yucheng’s ACDCD, the QCR was calculated. The device had eight parts (ignoring small parts such as screws, nuts, gaskets, springs, etc.) as shown in Figure 7. The scoring was carried out by researchers with a master’s degree in an anonymous style according to the method in Section 2.2. The structural strength connection relationship matrix is shown in Table 3. The functional strength connection relationship matrix is shown in Table 4 and the QCR is shown in Table 5. We had stronger functional requirements than structural, thus, here, $\alpha = 0.7$.

Table 3. Connection relationship matrix of structural strength.

| P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 |
|----|----|----|----|----|----|----|----|
| 0  | 4  | 0  | 0  | 0  | 0  | 0  | 0  |

Figure 9. A 3D exploded diagram of the improved ACDCD.

| Number | Description          |
|--------|----------------------|
| P1     | Air fan              |
| P2     | No.1 Air duct        |
| P3     | No.2 Air duct        |
| P4     | No.3 Air duct        |
| P5     | Injection box        |
| P6     | No.4 Air duct        |
| P7     | No.5 Air duct        |
| P8     | No.6 Air duct        |

Table 4. Connection relationship matrix of functional strength.

| Number | Description          |
|--------|----------------------|
| P9     | No.7 Air duct        |
| P10    | The upper right IC   |
| P11    | The upper left IC    |
| P12    | The left IC          |
| P13    | The right IC         |
| P14    | Fixed bracket        |
In the case of Li Yucheng’s ACDCD, the QCR was calculated. The device had eight parts (ignoring small parts such as screws, nuts, gaskets, springs, etc.) as shown in Figure 7. The scoring was carried out by researchers with a master’s degree in an anonymous style according to the method in Section 2.2. The structural strength connection relationship matrix is shown in Table 3. The functional strength connection relationship matrix is shown in Table 4 and the QCR is shown in Table 5. We had stronger functional requirements than structural, thus, here, $\alpha = 0.7$.

**Table 3.** Connection relationship matrix of structural strength.

| Number | Description       | Number | Description       |
|--------|-------------------|--------|-------------------|
| P1     | Air fan           | P11    | No.7 Air duct     |
| P2     | No.1 Air duct     | P12    | No.2 Connecting duct |
| P3     | No.2 Air duct     | P13    | No.2 T-branch duct |
| P4     | Air distributed duct | P14    | No.8 Air duct     |
| P5     | No.3 Air duct     | P15    | No.9 Air duct     |
| P6     | No.4 Connecting duct | P16    | No.10 Air duct   |
| P7     | No.1 T-branch duct | P17    | The right IC     |
| P8     | No.4 Air duct     | P18    | The upper right IC |
| P9     | No.5 Air duct     | P19    | The upper left IC |
| P10    | No.6 Air duct     | P20    | The left IC       |

**Table 4.** Functional strength connection relation matrix.

| Number | Description       | Number | Description       |
|--------|-------------------|--------|-------------------|
| P1     | 0                 | P2     | 2                 |
| P2     | 4                 | P3     | 0                 |
| P3     | 0                 | P4     | 4                 |
| P4     | 0                 | P5     | 0                 |
| P5     | 0                 | P6     | 0                 |
| P6     | 0                 | P7     | 0                 |
| P7     | 0                 | P8     | 0                 |

**Figure 9.** A 3D exploded diagram of the improved ACDCD.
Table 5. Quantitative connectivity matrix.

|     | P1  | P2  | P3  | P4  | P5  | P6  | P7  | P8  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| P1  | 0   | 2.6 | 0   | 0   | 0   | 0   | 0   | 0   |
| P2  | 2.6 | 0   | 2.6 | 0   | 0   | 0   | 0   | 0   |
| P3  | 0   | 2.6 | 0   | 4   | 0   | 0   | 0   | 0   |
| P4  | 0   | 0   | 4   | 0   | 7.4 | 0   | 0   | 0   |
| P5  | 0   | 0   | 0   | 7.4 | 0   | 6   | 0   | 0   |
| P6  | 0   | 0   | 0   | 0   | 0   | 7.4 | 0   | 0   |
| P7  | 0   | 0   | 0   | 0   | 6   | 7.4 | 0   | 7.4 |
| P8  | 0   | 0   | 0   | 0   | 0   | 0   | 7.4 | 0   |

4.2. Modular Process of ACDCD

Based on the modular method of improved spectral clustering described in Section 2.3, Li Yucheng’s ACDCD, Zongtao Liu’s ACDCD and the IACDCD were modularized, respectively. The improved spectral clustering modular algorithm was programmed using the python language, and the main configuration of the running computer was as follows: CPU, i7-1070 0F; Memory, 16 GB; GPU, NVIDIA RTX2060. The similarity matrix was calculated on the basis of the QCR in Section 4.1, and the affinity matrix was calculated using the full connection method. The degree matrix $D$ and the Laplacian matrix $L$ were constructed, and the $F$ corresponding to the first $k$ eigenvalues of $D^{-1/2}LD^{-1/2}$ was solved. Finally, the K-means clustering algorithm was used to cluster the $F$.

The ISCA had two main independent variables, which were the gamma ($\sigma$) and the cluster number($n_{clusters}$). Gamma took {0.001, 0.01, 0.1, 1, 5, 10, 100}. Because there were fewer parts of Li Yucheng’s ACDCD, the cluster number took {3, 4, 5}. The cluster numbers of the other two ACDCDs took {3, 4, 5, 6}. On this basis, a conventional spectral clustering modularization method was used for comparison to verify the effectiveness of the proposed method. The conventional spectral clustering modularity method did not consider the complex connection relationship when calculating the similarity matrix, and only used $1$ or $0$ to characterize the connection relationship between components. The Calinski–Harabasz Score (CHS) was used to evaluate the quality of the clustering results. The CHS evaluated the effect of clustering by the degree of dispersion between categories versus the degree of density within categories, which was calculated as follows

$$CH(k) = \frac{\text{tr}(B_k)}{\text{tr}(W_k)} \cdot \frac{m-k}{k-1}$$

where $m$ represents the number of training samples; $k$ represents the cluster number; $B_k$ represents the covariance matrix between categories; $W_k$ represents the covariance matrix between categories; $\text{tr}$ represents the trace of the matrix. The larger the value of the CHS, the better the effect of clustering.

For the above three ACDCDs, different gamma and $n_{clusters}$ combinations were applied, and two different clustering algorithms were used for modular processing. The clustering effect was assessed by calculating the CHS. Each combination was calculated five times, and the mean value of the CHS was taken.

4.3. Comparison and Analysis of Clustering Methods

In this section, the ISCA and the SCA were analyzed by comparing the specific gamma and different cluster numbers. Figure 10 shows the CHS bar diagram of two SCA for the ACDCD proposed by Yucheng Li at gamma = 0.01. Figure 11 shows the CHS bar diagram of two SCA for the ACDCD proposed by Zongtao Liu at gamma = 0.01. Figure 12 shows the CHS bar diagram of two SCA for the IACDCD at gamma = 0.01.
From Figure 10, the ISCA performed significantly better than the SCA when the cluster numbers were 3 and 4. The ISCA was not as satisfied as the SCA when the cluster number was 5. From Figure 11, the ISCA was better than the SCA when the cluster numbers were 3–5. The ISCA was not as satisfied as the SCA when the cluster number was 6. From Figure 12, the ISCA was more effective than the SCA. Moreover, the ISCA was obviously superior to the SCA when the cluster number was small. However, the ISCA had no obvious advantage and was not as satisfied as the SCA (Figure 10 the cluster number of 5; Figure 11 the cluster number of 6) when the cluster number was large. The difference between the ISCA and the SCA was the difference of the similarity matrix. The ISCA strengthened the connection relationship between parts, which made the connection relationship between parts obviously different. This difference was greatly reflected when the cluster number was small. However, for the ACDCD, the number of parts and the cluster number were small generally. Therefore, the ISCA was more effective than the SCA when both the number of components and the cluster number were small.
Figure 11. CHS bar diagram of two SCA for ACDCD proposed by Zongtao Liu at gamma = 0.01.

Figure 12. CHS bar diagram of two SCA for IACDCD at gamma = 0.01.

4.4. Comparison and Analysis of Clustering Quantity

In this section, the ISCA was used to analyze the optimal number of clusters by comparing different gamma values. Figure 13 shows the CHS bar diagram of the three cluster numbers of Yucheng Li’s ACDCD in different gamma cases. Figure 14 shows the CHS bar diagram of the four cluster numbers of Zongtao Liu’s ACDCD in different gamma cases. Figure 15 shows the CHS bar diagram of the four cluster numbers of the IACDCD in different gamma cases.

Figure 13. CHS bar diagram of three clusters of ACDCD proposed by Yucheng Li under different gamma.

Figure 14. CHS bar diagram of four clusters of ACDCD proposed by Zongtao Liu under different gamma.

Figure 15. CHS bar diagram of four clusters of IACDCD under different gamma.
4.5. Comparison and Analysis of Actual Results

Based on the optimal cluster results of Section 4.4, for Yucheng Li's ACDCD, the cluster results were \{1, 2\}, \{3, 4, 5\}, \{6, 7, 8\} when the cluster number was 3. Among them, the difference between the various gamma was whether part 5 was a class of \{6, 7, 8\}. From the actual analysis, dividing the IC into one class and the ventilation tube into one class was reasonable. Whether the injection box was clustered in the IC could be determined according to the actual connection. \{3, 4, 5\} was divided based on three categories' results when the cluster number was 4. The cluster results were \{1, 2\}, \{3, 4\}, \{5\}, \{6, 7, 8\} when the cluster number was 4. There was no need for modularity in five categories. Based on the optimal cluster results of Section 4.4, for Zongtao Liu's ACDCD, the cluster results were \{1, 2, 3, 5, 14\}, \{4, 6, 7, 8, 9\}, \{10, 11, 12, 13\} when the cluster number was 3. From the actual analysis, dividing the IC into one class and the ventilation tube leading to the IC into one class was reasonable. The cluster results were \{1, 3\}, \{2, 5, 14\}, \{4, 6, 7, 8, 9\}, \{10, 11, 12, 13\}.

From Figure 13, the effect of dividing into three categories was better than the other two categories. When the cluster number was 3, the cluster effect became inferior with the increase in gamma, and the cluster effect was unchanged within a certain range of gamma. The optimal gamma was \{0.001, 0.01, 0.1, 1\}. When the cluster number was 4, the cluster effect generally became superior with the increase in gamma, and the cluster effect was unchanged within a certain range of gamma. The optimal gamma was \{10, 100\}. When the cluster number was 5, the cluster effect generally became superior with the increase in gamma, and the cluster effect was unchanged within a certain range of gamma. The optimal gamma was \{5\}. From Figure 14, the effect of the cluster deteriorated as the cluster number increase. When the cluster number was 3, the cluster effect became superior with the increase in gamma and the cluster effect was unchanged within a certain range of gamma. The optimal gamma was \{100\}. When the cluster number was 4, the cluster effect became inferior with the increase in gamma and the cluster effect was unchanged within
a certain range of gamma. The optimal gamma was \(0.001, 0.01, 0.1\). When the cluster number was 5, the cluster effect generally became inferior with the increase in gamma and the cluster effect was unchanged within a certain range of gamma. The optimal gamma was \(0.001, 0.01\). When the cluster number was 6, the cluster effect generally became inferior with the increase in gamma and the cluster effect was unchanged within a certain range of gamma. The optimal gamma was \[1\]. From Figure 15, the effect of cluster deteriorated with the cluster number increase. When the cluster number was 3, the cluster effect became inferior with the increase in gamma and the cluster effect was unchanged within a certain range of gamma. The optimal gamma was \(0.001, 0.01, 0.1\). When the cluster number was 4, the cluster effect became inferior with the increase in gamma and the cluster effect was unchanged within a certain range of gamma. The optimal gamma was \(0.001, 0.01, 0.1\). When the cluster number was 5, the cluster effect was unchanged in general. The optimal gamma was \(0.001\). When the cluster number was 6, the classification effect generally became superior with the increase in gamma and the cluster effect was unchanged within a certain range of gamma. The optimal gamma was \(0.1\). The classification effect was not significant when the gamma was \(0.1\).

4.5. Comparison and Analysis of Actual Results

Based on the optimal cluster results of Section 4.4, for Yucheng Li’s ACDCD, the cluster results were \(\{1, 2\}\), \(\{3, 4, 5\}\), \(\{6, 7, 8\}\) when the cluster number was 3. Among them, the difference between the various gamma was whether part 5 was a class of \(\{6, 7, 8\}\). From the actual analysis, dividing the IC into one class and the ventilation tube into one class was reasonable. Whether the injection box was clustered in the IC could be determined according to the actual connection. \(\{3, 4, 5\}\) was divided based on three categories’ results when the cluster number was 4. The cluster results were \(\{1, 2\}\), \(\{3, 4\}\), \(\{5\}\), \(\{6, 7, 8\}\) when the cluster number was 4. There was no need for modularity in five categories. Based on the optimal cluster results of Section 4.4, for Zongtao Liu’s ACDCD, the cluster results were \(\{1, 2, 3, 5, 14\}\), \(\{4, 6, 7, 8, 9\}\), \(\{10, 11, 12, 13\}\) when the cluster number was 3. From the actual analysis, dividing the IC into one class and the ventilation tube leading to the IC into one class was reasonable. The cluster results were \(\{1, 3\}\), \(\{2, 5, 14\}\), \(\{4, 6, 7, 8, 9\}\), \(\{10, 11, 12, 13\}\) when the cluster number was 4. The cluster results were \(\{1, 2, 3, 4\}\), \(\{5\}\), \(\{6, 7, 8, 9\}\), \(\{10, 11, 12, 13\}\), \(\{14\}\) when the cluster number was 5. The cluster results were \(\{1, 2\}\), \(\{3, 4\}\), \(\{5\}\), \(\{6, 7, 8, 9\}\), \(\{10, 11, 12, 13\}\), \(\{14\}\) when the cluster number was 6. In combination with the actual situation, the results of five categories were most reasonable. Based on the optimal cluster results of Section 4.4, for IACDCD, the cluster results were \(\{1, 2, 3, 4, 5, 11\}\), \(\{6, 7, 8, 9, 10, 12, 13, 14, 15, 16\}\), \(\{17, 18, 19, 20\}\) when the cluster number was 3. From the actual analysis, dividing the IC into one class and the ventilation tube into one class was more reasonable. \(\{6, 7, 8, 9, 10, 12, 13, 14, 15, 16\}\) was divided into \(\{6, 8, 9, 10, 12, 14, 15, 16\}\) and \(\{7, 13\}\) based on the results of three categories when the cluster number was 4. The cluster results were \(\{1\}\), \(\{2, 3, 4, 5, 11\}\), \(\{6, 8, 9, 10, 12, 14, 15, 16\}\), \(\{7, 13\}\), \(\{17, 18, 19, 20\}\) when the cluster number was 5. \(\{6, 8, 9, 10, 12, 14, 15, 16\}\) was divided into \(\{6, 8, 10, 12, 14, 16\}\) and \(\{9, 15\}\) based on the results of five categories when the cluster number was 6. In combination with the actual situation, the results of five categories were most reasonable.

Modularity has an important characteristic that worn parts of the product could be diagnosed, maintained, isolated and replaced. For the important functions, costly maintenance and vulnerable parts of the product especially, the modularity could minimize the using cost and maintenance cost [26]. From the analysis of the optimal division of the above modules, the IC was divided as a module. It was proved that modularizing the IC for the ACDCD was necessary. Moreover, as an important component, the size of the IC varies with the size of the tunnel and the roadheader. Therefore, unifying the IC was necessary. The IACDCD unified the design of the IC to realize the purpose of easy replacement, easy maintenance and an iterative design of the IC while ensuring IC function to the greatest extent. Moreover, the splicing of more complex functions could be achieved because of the characteristics of the IC proposed in this paper. As shown in Figure 16, an air curtain
barrier can be set in front of the driver to further enhance the dust isolation effect of the ACDCD.

![Figure 16. Comprehensive evaluation results.](image)

Through the modular process of the ACDCD, the core components and common components were designed in a unified manner avoiding the repeated work of iterative design, reducing the labor intensity of designers, greatly reducing the design cycle of products and improving the production efficiency of products. Meanwhile, the IACDCD can quickly and economically design efficient and reliable products for different scenarios.

5. Conclusions

The air curtain dust control device is an important device to protect the driver from high concentrations of dust generated by the roadheader. The existing ACDCD are customized for different roadheaders and the different production conditions, and are not flexible enough and are difficult to industrialize. Aimed at the above problems, we proposed a modular method of ACDCD based on improved spectral cluster module division and proposed an IACDCD. The following conclusions can be summarized:

1. An improved ACDCD was proposed in this paper to adapt to more application scenarios, reduce the complexity of the ACDCD and improve the flexibility of the ACDCD. The injection box and the fixed bracket were removed. The IC size and the pipeline system were unified. Moreover, the angle of the individual ICs was adjusted by a bolt that connected the IC to the fixed bracket.

2. We proposed a modular method of ACDCD based on the improved spectral cluster algorithm (ISCA) module division. A similarity matrix construction method considering the functional and structural correlation matrix of components was proposed to strengthen the connection relationship of components. The ISCA was more effective than the SCA when both the number of components and the cluster number were small.

3. The two existing ACDCDs and the IACDCD were modularized using the improved spectral cluster module division method. From the analysis of the optimal division, it was proved that modularizing the IC for the ACDCD was necessary. As an important component, the size of the IC varies with the size of the tunnel and the roadheader. Therefore, unifying the IC was necessary. The IACDCD unified the design of the IC to realize the purpose of easy replacement, easy maintenance and the iterative design of the IC while ensuring IC function to the greatest extent.

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