Assessment of volatile organic pollution control technologies in automotive industry

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Abstract. Volatile organic compounds (VOCs) are one of the main factors causing air pollution in China. In the automotive industry, spraying, drying, and other processes will produce a large amount of VOCs pollution. How to select suitable treatment techniques is the major problem for VOCs control. In this paper, a treatment technology evaluation index system was constructed based on the characteristics of VOCs emission in automobile manufacturing. Using the Analytic Hierarchy Process (AHP) model to comprehensively evaluate VOCs governance technologies in the automotive industry. The results showed that the priority of the six VOCs treatment techniques is as follows: runner + RTO > activated carbon + TO > activated carbon + RTO > runner + RCO > activated carbon + CO > activated carbon + RCO.

1. Introduction
Volatile Organic Compounds (VOCs) are defined as organic compounds that participate in atmospheric photochemical reactions, or as organic compounds defined in accordance with relevant regulations. In the process of atmospheric chemical reaction, VOCs can significantly change the physical and chemical properties of the atmosphere, and harm the atmospheric environment through long-distance transmission across the border. Through the analysis of air pollution sources, VOCs are important precursor substances that affect the generation of secondary organic aerosols, PM2.5 and ozone [1]. The photochemical smog caused by VOCs is harmful to human body and plant health. Benzene, toluene, xylene and other benzene series of the VOCs are irritating to the human respiratory tract, sensory system and skin, have harmful effects on the human viscera and nervous system, and can even produce three effects on the human body [2].

In recent years, VOCs have become the focus of China's air pollution prevention and control work, The "13th Five-Year" Volatile Organic Matter Pollution Prevention and Control Work Plan "proposes that during the" 13th Five-Year "period, the total VOCs emissions in key regions and key industries should be reduced by more than 10%. As a key industry, the automobile manufacturing industry is required to promote VOCs emission control in vehicle manufacturing, auto parts manufacturing and other fields, and to build efficient terminal treatment facilities to achieve emission standards. At present, VOCs terminal treatment technologies is mainly divided into recovery technologies and destruction technologies. Recovery technologies includes activated carbon adsorption-desorption, solvent absorption, condensation method, etc. Destruction technologies includes combustion method, plasma flame method, biodegradation method, and concentration-combustion technologies. Different technologies have certain differences in governance effect, application object, and scope of application. Different enterprises have different characteristics of VOCs emission sources, so it is necessary to choose targeted VOCs governance technologies. Therefore it is necessary to establish an evaluation
system of VOCs governance technologies in the automotive manufacturing industry and provide a scientific technology selection method for VOCs governance in the industry.

The Analytic Hierarchy Process (AHP) is one of the most commonly used and effective group decision-making methods for technology selection, which is used to evaluate complex multi-standard decision-making methods involving subjective judgment [3][4]. AHP has been applied in the selection of VOCs treatment technologies in oil storage and transportation, packaging, and printing industries [5,6]. In this paper, VOCs treatment technologies evaluation index is selected according to the emission characteristics of the automobile manufacturing industry, and the weight of the evaluation index of VOCs treatment technologies is calculated by using AHP, and a complete evaluation model is constructed, which provides a reference for the selection of VOCs treatment technologies of automobile manufacturing enterprises in the future.

2. Materials and Methods

2.1. Evaluation methods

The AHP method has been widely used in safety science, environmental science, and other fields [7]. The AHP method builds the process of decision problem into an analytic hierarchy model that includes decision target layer, evaluation criterion layer (i.e., first-level indicator layer), second-level indicator layer and the alternative scheme layer to be evaluated. By solving the eigenvector of the judgment matrix, the weight of each element in each level of the model is obtained for the corresponding elements in the next level. The index weight is normalized and the weight of the lowest index relative to the decision target is obtained. Determining the pros and cons of each index of the alternative scheme, and determining the weight of each scheme under each index through the judgment matrix, and calculating the final score of each scheme for the decisive goal through the way of weighted sum, the highest score is identified as the optimal technology. The basic steps are as follows [8]: (1) To establish an analytic hierarchy model with three levels, including decision target layer, index layer, and alternative technology layer. (2) Construction of judgment matrix. (3) Calculate the ranking weight vector of the first-level index and the second-level index and carry out a consistency check. (4) Calculate the final score of the alternative plan for the decisive goal. (5) Evaluate the scheme according to the final calculation results.

2.2. Evaluate technical route

With the ultimate goal of pollutant emission reaching the standard in a long term and stably, a pollution control technology evaluation model was established that comprehensively considered the pollution treatment capability, input and operation cost, technologies maturity, and other indicators of different technology paths. The main steps are shown in Figure 1.
3. Results and discussion

3.1. VOCs emission characteristics of automotive manufacturing industry

VOCs pollution in the automotive industry is mainly caused by the use of solvent-containing products such as coatings and cleaning agents. According to the report released by China Coatings Industry Association, in 2017, China produced 28 million cars and 1.7 million tons of vehicle coatings, among which the proportion of paint used by car manufacturers (original OEM paint) was 53-54%, about 900,000 tons. In the production of various coatings, the proportion of water-based paint with a solvent content of 10% is 2/3, and that of oil-based paint with a solvent content of 50% is 1/3. The total consumption of solvent in the automobile manufacturing industry is about 210,000 tons. In the process of vehicle manufacturing, primer spraying, middle coating, top paint spraying, leveling, drying, and other processes will cause a large number of VOCs emissions. In the process of automobile

Figure 1. Technologies assessment roadmap.

A) Technical preliminary screening. Through data, literature research, and field investigation, the available pollution control technologies is selected, and some unsuitable VOCs treatment technologies is eliminated through the characteristic parameters of enterprise pollution emission, and the list of alternative VOCs treatment technologies is formed.

B) Technical index system determination. Selected technical index, economic index, environmental index, and other first-level evaluation indexes, and refined the second-level evaluation index. Build pairwise judgment matrix, invite experts to score the importance of the index according to the order of the first level index and the second level index, and normalize the importance of the second-level index to get the weight of the decision goal, to determine the evaluation index system of VOCs governance technologies.

C) The technical index score is determined. In this study, through the preliminary investigation and expert evaluation of VOCs governance technologies, combined with pairwise judgment matrix to calculate the secondary index scores of each alternative technologies.

D) Technical score calculation. Input each VOCs governance technology index weight and score, use linear weighted sum method to calculate the score of alternative technology for the decision goal, according to the final score, determine the priority of VOCs governance technology.
manufacturing, spraying, and drying VOCs pollution production links and their pollution production characteristics are shown in Table 1.

| process        | methods                              | Air volume (m³/h) | concentration concentration | VOCs emission ratio | characteristics               |
|----------------|--------------------------------------|-------------------|----------------------------|---------------------|------------------------------|
| Spraying       | Primer                               | Closed, 75%       | Low                        | 60-85%              | Moisture content is high      |
|                | Primer surfacer                      | internal circulation, 15% fresh air | 150000-700000              |                     |                              |
|                | Base coat                            |                   |                            |                     |                              |
|                | Clear coat                           |                   |                            |                     |                              |
| Drying         | Electrophoresis drying               | Closed, centralized discharge through the exhaust system | 3000-60000             | The relatively high   | 10-15%                       |
|                | Primer surfacer drying               |                   |                            |                     |                              |
|                | Clear coat drying                    |                   |                            |                     |                              |

3.2. Evaluation of VOCs control technologies in the automotive manufacturing industry

According to the technical assessment route, this section evaluates the optimal control technology of VOCs treatment in the spraying process of the automotive manufacturing industry.

3.2.1. The technology of primary. According to the preliminary investigation, the scope of application of VOCs governance technologies is sorted out, and the specific scope of application of VOCs is shown in Figure 2.

Due to the complexity of VOCs waste gas composition and nature and the limitations of a single treatment technology, in many cases, the use of a single technology is often difficult to meet the treatment requirements, but also uneconomic. Using the advantages of different treatment technologies, the combined treatment process can not only meet the emission requirements, but also reduce the operating cost of purification equipment. Therefore, in recent years, the combination of two or more purification technologies in the treatment of organic waste gas has received great attention, and has
been rapidly developed. For example, the combined process of condensation and adsorption can be adopted for the treatment of high concentration organic waste gas. Low concentration organic waste gas can adopt the combined process of adsorption concentration and condensation recovery or incineration, etc. Usually, we can choose the appropriate end treatment technology according to the composition of pollutants, the nature of pollutants and the discharge conditions (air volume, concentration, temperature, particulate matter content, etc.).

Combined with the characteristics of production and pollution of large air volume and low concentration of VOCs exhaust gas produced by automobile manufacturing spraying process, the candidate VOCs treatment technologies was screened and eliminated. After the elimination, Suitable for spraying process treating technologies belong too the adsorption of VOCs concentration + thermal combustion type device, containing activated carbon concentration + TO, activated carbon concentration + CO, activated carbon concentration + RTO, activated carbon concentration + RCO, wheel enrichment + RTO, wheel enrichment + RCO. The preliminary screening results and descriptions of VOCs technologies evaluation are shown in Table 2.

| Processing technologies         | Feasibility | Instructions                                      |
|---------------------------------|-------------|--------------------------------------------------|
| Adsorption recycling            | ×           | Subsequent combustion treatment is required       |
| Adsorption concentration        | ×           | Subsequent combustion treatment is required       |
| Biological treatment            | ×           | Operating temperature is too low                 |
| Low temperature Plasma technology| ×           | Operating exhaust volume and temperature range is too narrow |
| Condensate recovery             | ×           | Operating concentration is too high              |
| RTO                             | ×           | Spraying exhaust gas concentration is too low    |
| RCO                             | ×           | Spraying exhaust gas concentration is too low    |
| Adsorption concentration + thermal combustion | ✓           | Adsorption includes activated carbon and runner concentration, combustion includes RTO, RCO, etc |

### 3.2.2. AHP evaluation model construction

According to the decision target and the VOCs technologies evaluation index system composed of the first and second level indicators of VOCs governance technologies, an AHP analysis hierarchy structure model is constructed, including the decision target layer, the first level indicator layer, the second level indicator layer and the alternative technologies layer. The analysis hierarchy model is shown in Figure 3.

![Figure 3. VOCs governance technologies evaluation analysis hierarchy model.](image-url)
According to the expert assignment results of index weight, combining the research of VOCs treatment technologies, in view of the primary index layer (B1, B2, B3), secondary index layer (B11, B12, B13, B14, B15, B21, B22, B23, B31, B32) as well as the solution layer (S1, S2, S3, S4, S5, S6) two judgment matrix structure, after the completion of the need to construct judgment matrix with consistency check, calculate the weight of each layer elements relative decision-making target. Take the first-level index weight judgment matrix R1 as an example.

\[
\text{R1} = \begin{bmatrix}
1 & 3 & \frac{1}{5} \\
\frac{1}{3} & 1 & \frac{1}{7} \\
5 & 7 & 1
\end{bmatrix}
\]

(1)

The maximum characteristic root of \( R_1 \) \( \lambda_{\max} = 3.0658 \), and its characteristic vector \( W = (0.1932, 0.0833, 0.7235) \), of which three components are the weight values of three elements B1, B2, and B3 in the first-level indicator layer B relative to the decision target. According to the consistency test formula of the judgment matrix:

\[
C_i = (\lambda_{\max} - n)/(n-1)
\]

(2)

\[
C_i = 0.0329
\]

(3)

Find the random consistency index \( R_i \), when \( n = 3 \), \( R_i = 0.58 \), \( C_R = C_i/R_i = 0.0567 \) is less than 0.1, so the matrix conforms to the consistency test, and the index weight value in W can be applied.

Under the first-level index B1, \( \lambda_{\max} = 5.3965 \), corresponding eigenvector \( W_1 = (0.0822, 0.1674, 0.2766, 0.0483, 0.4256) \). Among them, the five components are the weight values of the five elements in the second-level indicator layer B: B11 maturity, B12 stability, B13 applicability, B14 complexity and B15 security. The calculated consistency test index \( C_r = 0.085 \), less than 0.1.

Under the first-level index B2, \( \lambda_{\max} = .0183 \), corresponding eigenvector \( W_2 = (0.3202, 0.5571, 0.1126) \). Among them, the three components are the weight values of the three elements in the second-level indicator layer B: B21 construction cost, B22 operation cost, B23 floor area. The calculated consistency test index \( C_r = 0.0176 \), less than 0.1.

Under the first-level index B3, \( \lambda_{\max} = 2 \), corresponding eigenvector \( W_3 = (0.75, 0.25) \). Among them, the two components are the weight values of the two elements in the second-level indicator layer B: B31 removal efficiency, B32 secondary pollution. The calculated consistency test index \( C_r = 0.0002 \), less than 0.1.

The weight of all indexes in the second-level index layer is normalized to get the weight value of each second-level index relative to the decision target. The specific weight values of secondary indicators are shown in Table 3.

| First level indicator | Secondary indicators | Weight |
|-----------------------|----------------------|--------|
| Technical indicators  | Maturity level        | 0.0159 |
|                       | Stable level          | 0.0323 |
|                       | Applicable level      | 0.0534 |
|                       | Complex level         | 0.0093 |
|                       | Security level        | 0.0822 |
| Economic indicators   | Construction costs    | 0.0267 |
|                       | Operating costs       | 0.0464 |
|                       | Construction area     | 0.0102 |
| Environmental indicators | Removal efficiency | 0.5426 |
|                       | Secondary pollution   | 0.1809 |
Combined with experts on the VOCs governance technologies of each secondary index evaluation, the use of judgment matrix VOCs governance technologies index score. The scores of activated carbon concentration + TO, activated carbon concentration + CO, activated carbon concentration + RTO, activated carbon concentration + RCO, runner concentration + RTO, runner concentration + RCO are shown in Table 4.

### Table 4. VOCs governance technologies index scores.

| Alternative technologies | Maturity level | Stable level | Applicable level | Complex level | Security level | Construction costs | Operating costs | Construction area | Removal efficiency | Secondary pollution |
|---------------------------|---------------|--------------|------------------|---------------|----------------|--------------------|----------------|------------------|-------------------|-------------------|
| Activated carbon + RTO    | 0.1667        | 0.1244       | 0.2455           | 0.1073        | 0.0723         | 0.2217             | 0.1461         | 0.0405           | 0.2356            | 0.1005            |
| Runner + RTO             | 0.1667        | 0.3767       | 0.2693           | 0.4388        | 0.391          | 0.103              | 0.1461         | 0.0824           | 0.2356            | 0.1005            |
| Activated carbon + RCO   | 0.1667        | 0.0534       | 0.0761           | 0.044         | 0.1034         | 0.0744             | 0.3045         | 0.2193           | 0.0755            | 0.2389            |
| Runner + RCO             | 0.1667        | 0.2112       | 0.0818           | 0.1191        | 0.2264         | 0.0415             | 0.3045         | 0.2193           | 0.0755            | 0.2945            |
| Activated carbon + TO    | 0.1667        | 0.1576       | 0.2455           | 0.2069        | 0.089          | 0.3776             | 0.0365         | 0.2193           | 0.2541            | 0.0600            |

The VOCs governance technologies index score and the index weight through the linear weighted sum method to get the total score of VOCs governance technologies, the final automotive manufacturing industry spraying process VOCs governance technologies score ranking is: wheel concentration + RTO > activated carbon concentration + TO > activated carbon concentration + RTO > wheel concentration + RCO > activated carbon concentration + CO > activated carbon concentration + RCO. The specific evaluation results are shown in Table 5.

### Table 5. VOCs Management technologies evaluation results.

| Alternative technologies | Weight | sequence |
|--------------------------|--------|----------|
| Runner + RTO             | 0.2219 | 1        |
| Activated carbon + TO    | 0.1929 | 2        |
| Activated carbon + RTO   | 0.1859 | 3        |
| Runner + RCO             | 0.1453 | 4        |
| Activated carbon + CO    | 0.1343 | 5        |
| Activated carbon + RCO   | 0.1199 | 6        |

Through the analysis of the scores of alternative technologies, it is found that the runner concentration + RTO technology has more outstanding advantages in technical indicators, and the comprehensive evaluation score is higher. However, its economic index has a great disadvantage compared with the runner concentration + RCO. Therefore, based on meeting the VOCs emission standard of exhaust gas emission concentration, the technologies with an operating cost advantage can be selected: runner concentration + RCO technology. The results show that the evaluation of VOCs governance technologies needs to make decisions from many aspects. Enterprises can adjust the weight parameters of each index in the model according to their needs and select the optimal VOCs governance technologies in line with their actual situation.

### 4. Conclusion

With the gradual tightening of China's environmental standards, it is necessary to establish a systematic and scientific-technical evaluation index system to support the screening of VOCs governance technologies. In this study, the VOCs treatment technology evaluation index system of the automotive manufacturing industry was constructed and combined with AHP to evaluate the VOCs treatment technology of the spraying process. Wheeler concentration + RTO technology has advantages in technical indicators and environmental indicators and is selected as the optimal
treatment technology. From the perspective of practical application, the result is more reasonable. The technology evaluation model in this study can be adjusted according to the actual needs of enterprises, which provides strong scientific support for the selection of VOCs governance technology in the industry. At the same time, it is necessary to continue to study the VOCs governance technologies evaluation model in the automotive industry in this paper. The next step can be carried out from the following aspects:

(1) The VOCs governance technologies index database is constructed, the evaluation index value is revised according to the technologies development, and the evaluation system is updated.

(2) Expand the evaluation index system, build the characteristic evaluation model in different situations, and customize the evaluation model of VOCs governance technology for enterprises with different needs.

(3) Starting from the pollution control of the whole process of the automobile manufacturing industry, the evaluation model of combined pollution treatment technologies is constructed to provide the best pollution control scheme of the whole process for enterprises.

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