1 | INTRODUCTION

The concept of eco-efficiency was originally proposed by the Canadian Scientific Council (SCC) in the 1970s. In the 1980s, the International Union for Conservation of Nature and Natural Resources (IUCN) introduced ecological efficiency into the strategy of global conservation. In 1992, Swiss scholars, Schaltegger and Sturn, provided the definition of ecological efficiency. Later 1990s, different organizations and scholars in the world started to study the ecological efficiency, and offered various definitions for ecological efficiency. The most influential definition for eco-efficiency is the one given by the World’s Sustainable Development of industrial and commercial enterprises Commission (WBCSD) in 1995. The focal point of eco-efficiency is to reduce the intensity of resources and energy use, increase the efficiency of environmental protection and resource utilization.
of using renewable resources, enhance the recovery of substances, and reduce the emission of toxic substances. The intensity of resource consumption and the pollution of the environment are reduced to the level that is consistent with the ecological carrying during the entire life cycle of an enterprise. In 2000, the connotation was further clarified and three major goals were set. One is to reduce resource consumption and the other is to reduce the impact on the environment. The third is to increase product value.

The concept of carrying capacity originates from the theory of natural ecology, which refers to the maximum living of a certain organism under certain environmental conditions. In the 1920s, ecologists introduced the concept of carrying capacity into the field of human ecology. Park published the principle of carrying capacity and proposed the concept of ecological carrying capacity, that is, the maximum limit of the number of individuals exist in a given environment. Subsequently, the theory and application of carrying capacity continue to evolve, and the concept of carrying capacity continues to expand. Then, the concept of carrying capacity was applied to measure the relationship between industrial economy and resources, environment, and social conditions. In 1995, Arrow, the winner of the Nobel Prize in economics, with other prominent economists and ecologists published an article entitled “Economic Growth, Capacity and Environment” in the Science magazine, which arouses a lots of research interests in the carrying capacity by academicians and politicians. Bishop first proposed the concept of environmental carrying capacity in 1974. He argued that environmental carrying capacity reflects the intensity of human activities that a region can permanently sustain at an acceptable level. Schneider stressed that environmental carrying capacity is the capacity of natural or man-made environmental systems to accommodate population growth without serious degradation. Tang et al argued that the environmental carrying capacity is the threshold for the ability of a certain region to support the economic activities of human society under certain environmental conditions within a certain period of time. Peng et al argued that regional carrying capacity means that for a certain period of time and a certain region, the regional environmental system can bear the appropriate degree of socioeconomic activities under the condition of no significant change in the regional environmental system and the regional environmental function. Some scholars translated the ecological carrying capacity of environment into ecological carrying capacity. Therefore, the term of ecological carrying capacity is used in this paper.

The three-dimensional state-space model presented in this paper refers to the combination of the ecological bearing index model and the state-space model. It views petrochemical enterprises as pressurers on natural resources and the environment. It uses the economic status of the enterprises, the degree of resource usage, and the impact on environment by enterprises as three axes. The construction of three-dimensional geometric space, from economic, resource, and environmental aspects, describes the interaction and interrelationship between the three.

2 | ECO-EFFICIENCY EVALUATION INDEX SYSTEM

As an emerging management concept, eco-efficiency emphasizes that while realizing high profits, enterprises should take responsibility of environmental protection, improve their efficiency, cut down environmental pollution, and reduce operations cost. Based on the state-space model and the carrying capacity theory, the three-dimensional state-space ecological carrying capacity model describes the resource, economy, and environment interaction of a petrochemical enterprise from three aspects of economy, resources, and environment. In the three-dimensional state-space model, a petrochemical enterprise puts pressure on natural resources and social environment, and the three axes of the model represent the economic operation status of the petrochemical enterprise, the status of resource utilization, and the impact on the social environment. The model reflects the close relationship between business economics, resources, and the environment. Considering the characteristics of production technology of a petrochemical enterprise, the paper tries to achieve the goal of ecological efficiency, realize the requirement of sustainable development of the petrochemical enterprise, and construct the index system of eco-efficiency evaluation for petrochemical enterprises. The system includes state layer and variable layer, and chooses economy, resource, and environment as three indexes. The index system is shown in Table 1.

3 | MODEL ESTABLISHMENT

3.1 | Related model analysis

3.1.1 | Ecological footprint model

Canadian economist William Rees and his PhD student Mathis Wackernagel put forward the ecological footprint model for measuring the degree of sustainable development in the early 1990s. Ecological footprint analysis calculates the size of ecological footprint from the demand and calculates the carrying capacity from the supply. Through the comparison of the two, it evaluates the issue of the sustainable development. Ecological footprint is a widely used method for evaluating environmental carrying capacity. However, the current research on the evaluation of ecological footprint mainly focuses on the urban as well as the national level. The ecological footprint model compares bioproductive lands and
TABLE 1 Evaluation of index system for eco-efficiency of petrochemical enterprises

| Index type          | State layer                        | Variable layer                        |
|---------------------|------------------------------------|---------------------------------------|
| **Economics**       | Economic total and benefit          | Total assets                          |
|                     |                                    | Industrial output value               |
|                     |                                    | Total profit                          |
| Production technology and economy | Comprehensice commodity rate        | Crude oil processing loss rate        |
|                     |                                    | Material productivity                 |
| **Environment**     | Environmental pollution            | Oil content in sewage                 |
|                     |                                    | Sulfide content in sewage             |
|                     |                                    | Content of phenol in sewage           |
|                     |                                    | Single displacement of industrial sewage |
|                     |                                    | Exhaust emissions                     |
| Environmental management | Treatment rate of industrial waste water | Treatment rate of industrial waste gas |
| Resources            | Total resource                      | Application amount of water           |
|                     |                                    | Application amount of electrical energy |
|                     |                                    | Application amount of steam           |
| Resource utilization | Repetitive use rate of industrial water | Unit primary oil consumption       |
|                     |                                    | Comprehensive energy consumption     |

water areas converted from the human consumption of resources, production, and services (namely, the ecological footprint). It uses the equivalent factors to available bioproductive lands and water areas (namely, the carrying capacity) adjusted by yield factors on local, regional, or global scales for given populations, economic levels, or manufacturing technologies to assess ecosystem sustainability. According to the definition, biologically productive lands were divided into six categories: cropland, grassland, forestry, water area, built-up land, and fossil land. The ecological footprint method allows us to make comparisons to determine whether human production and consumption activities are within the local carrying capacity. Furthermore, the ecological footprint method has many advantages. For example, this method is not only concise and easy to understand and use but also available to regeneration and substitutability of natural resources including recycling and self-purification of life support systems and biodiversity conservation. Moreover, it provides a biophysical foundation to examine the state of human–ecosystem interactions and to survey the spatial features of ecosystem appropriation. Being one of the most influential quantitative methods, the ecological footprint method has been widely recognized and applied by international agencies, government departments, and research institutions and has even become the starting point for evaluating the sustainability of local, regional or national ecosystems. Luck proposed an urban funnel model based on different types of land occupancy in the ecological footprint and discussed the importance of urban location and the competition for ecological services among the cities. Barrett et al studied the issue of sustainable development in the region by combining material flow analysis with ecological footprint. Recep and David investigated policy shocks to ecological footprint of the USA. After the concept of ecological footprint was introduced to China in 1999, many Chinese scholars have been actively involved in this research. Xu and Zhang successively calculated the ecological footprint of Gansu Province and studied the ecological footprint of the 12 western provinces of China. Miao et al applied ecological footprint to evaluate ecological environment quality in Anhui province of China. Liu et al applied the improved ecological footprint method to assess the sustainability of the straw utilization cycle model. Peng et al evaluated the energy sustainability of Qingdao of China from 2004 to 2014 using the ecological footprint method. Ecological footprint analysis has its some advantages in theory and application. It is unique in evaluating human impacts on ecosystems. However, its analysis has ecological bias and focuses only on the sustainable development of a region. It does not provide further judgments for the sustainability of social subsystems and economic subsystems.

3.1.2 Ecological carrying index model

The capacity of the ecosystem support system depends on the three aspects of ecological resilience, resource carrying capacity, and environmental carrying capacity. The ecological carrying capacity model gives the basic indicators and the method of calculation. It also gives the expression and calculation methods of ecological carrying index, ecological pressure index, and ecological bearing pressure. Finally, it provides the comprehensive evaluation of regional ecological carrying capacity index selection and grading method. Gao used this method with geographic information system as a means to carry out an empirical study of ecological carrying capacity and sustainable development of the Hei He River Basin. He used this method combining grading and comprehensive evaluation methods to make the evaluation results clear and accurate. OuYang et al proposed the ecological carrying index to evaluate the bearing status of forest landscape resources. Gu et al used the pressure-state-response model to integrate the ecological footprint, ecological carrying capacity, and economic factors to obtain the comprehensive ecological carrying index, and applied it in the mining cities in Liaozhong of China from 1985 to 2005. However, this method requires a high degree of data collection and
processing and it does not explore the complexity among the elements of the system.

### 3.1.3  State-space model

It is known that the establishment of the state-space model is an effective method for quantitatively describing the state of a system by the Euclidean geometry space. Usually, the state-space model consists of the three-dimensional state-space axis that represents the state vector of each element of a system. In studying environmental carrying capacity, the three-dimensional state-space axis can represent the population, economic and social activities, resources, and environment, respectively. The points in space are the carrying state points, and the different points indicate the bearing state in different situations. The actual bearing conditions do not exactly match the ideal bearing capacity in the state space, there will usually be some deviations, resulting in three results of being overloaded, fully loaded, and loadable. In a specific case, the carrying state point of the state-space method can indicate the regional carrying status for a certain period. Using the vector modulus formed by system state points in the state space as the bearing capacity, the state-space method can quantitatively describe and measure the bearing capacity and bearing state of the object. In recent years, the state-space method has been gradually promoted and successfully applied to many fields such as military affairs, biomedicine, socio-economy, and human life. Yu et al\textsuperscript{39} used the state-space method to measure the system’s bearing capacity in the region. Sun et al\textsuperscript{40} applied the state-space model to estimate the ecological carrying capacity of Suiyang county in Guizhou province of China. The method of state-space model is more suitable for use in comprehensive evaluation of enterprises. Its three-dimensional model just fits the requirements of three aspects of economy, resources, and environment. However, the original model is not able to reflect the development of an enterprise itself. With the rapid development of science and technology, enterprises can adopt new alternative energy sources or reduce the consumption of resources and environmental pollution through restraining their own production activities to improve their carrying capacity.

#### 3.2  Build three-dimensional state-space model

Many researchers believe that enterprises in the pursuit of eco-efficiency process have three goals. First, the production needs to reduce the consumption of energy, materials, water, and land resources, and to improve product recycling and durability. Second, during the production and final product consumption it is necessary to minimize emissions, waste disposal and toxic substances, and other natural impact. Third, companies should try their best to increase the value of products or services, to provide customers with more benefits, and to improve their economic performance.

Based on the analysis of ecological footprint, ecological carrying index, and state-space model, this paper considers that the ecological efficiency status of petrochemical enterprises can be expressed by the bearing status of the enterprise’s carrying space, and the economic activities and bearing space of petrochemical enterprises can be described from three aspects, resources, economy, and environment. Thus, we build a three-dimensional state-space model of petrochemical companies, as shown in Figure 1.

In this three-dimensional state-space model, we can view petrochemical enterprises as pressure bearers of their carriers, through the in-depth analysis of the economic activities, resource utilization, and environmental conditions of petrochemical enterprises, and describe the state space in terms of resources, economy, and environment. The three axes of the space, points A, B, and C, represent the ecological carrying status points, while the ecological carrying status points reflect the bearing status of the enterprises within a certain period of time. The size of the carrying capacity of the enterprise can be represented by calculating the vector model consisting of the state space origin and the system ecological carrying status points.

The carrying capacity of the enterprise is

$$ECC = |M| = \sqrt{\sum_{i=1}^{n} (\omega_i x_i)^2}$$

(1)

where $ECC$ is the ecological carrying capacity of enterprise; $|M|$ is the vector mode; $x_i$ is the ideal state value ($i = 1, 2, \ldots, n$); $\omega_i$ is the weight of $x_i$.

The ecological efficiency of petrochemical companies can be represented by the bearing capacity of the company’s carrying space. In Figure 1, the surface is the bearing surface of the petrochemical enterprise. The point of higher than the bearing surface, such as point B, indicates that the enterprise is in an overload state. Points on the surface, such as point C, indicate that the enterprise is in a fully load state. Points lower than the surface, such as point A, indicate that the company is in a loadable state.\textsuperscript{41}

### 4  MODEL CALCULATION

#### 4.1  Model calculation steps

1. Determine the value of the carrying capacity of the enterprise, that is, the planned value or the ideal value, $ECC_i (i = 1, 2, \ldots, n)$.
2. Determine the weight of the index, $\omega_i_i (i = 1, 2, \ldots, n)$. 
3. Determine the status quo value of the index, 
\( ECS_i, (i = 1, 2, \cdots, n) \).

4. Structure vector, 
\( ECS_i^* = ECS_i(\text{opr})\cdot ECC_i \), 
\( ECS_i^* \) refers to the state of an enterprise. The indicator is overloaded when 
\( ECS_i^* > 1 \). The indicator is fully load when 
\( ECS_i^* = 1 \). The indicator is not fully loaded when 
\( ECS_i^* < 1 \). \( opr \) represents a certain operator, operation, or process operator on behalf of 
\( ECS_i^* \) when it takes different values.

5. Calculate the actual ecological pressure produced by the enterprise production. The weighted distance of the 
\( ECS_i^* \) point distance from the origin is \( D \) in the three-dimensional state space of economy, environment, and resources,
\[
D = \sqrt{\sum_{i=1}^{n} \left( \omega_i \cdot ECS_i^* \right)^2}
\]

6. Calculate the total ecological carrying capacity of enterprises,
\[
ECC = \sqrt{\sum_{i=1}^{n} \left( \omega_i \cdot ECC_i^* \right)^2} = \sqrt{\sum_{i=1}^{n} \omega_i^2 \cdot ECC_i^*} = 1.
\]

7. Judge the actual carrying status of the enterprise. The indicator is overloaded when \( D > ECC \). The indicator is fully loaded when \( D = ECC \). The indicator is not fully loaded when \( D < ECC \). \footnote{42,43}

4.2 | Example of petrochemical enterprise

We will use this petrochemical enterprise as an example to verify the feasibility of the three-dimensional state-space model applied to calculate the ecological efficiency of enterprises. This application can not only provide enterprises with a theoretical tool to judge their ecological efficiency, but also understand their ecological efficiency to formulate sustainable development decision-making. We will take the following steps to demonstrate our application:

1. Determine the Weight Using Analytic Hierarchy Process (AHP). The AHP method requires two steps. Step one is to ask the relevant experts to compare the importance of the index system and assign scores so as to build a judgment matrix, and then determine the subindicators’ contribution to the higher level indicators based on the eigenvectors of the matrix. Step two is to conduct the consistency test. In order to ensure the rationality and scientific of the indicator’s weights, the 10 experts were asked to score these indicators. The highest score and the lowest score were removed. After the consistency test, a group of indicators to determine the matrix is shown in Table 2.

The weight vector of the first level index is calculated to be \( (0.121, 0.341, 0.538)^T \), and the consistency is satisfactory after the consistency check. The two level index judgment matrix, as shown in Table 3.

Similarly, we calculated the weight vectors of the third-level indexes for each second-level index separately and tested their consistency. We obtained the weights of the indexes at all levels, and then determined the final weight of each index through the combined weights of the indexes at all levels. Indicator weights are shown in Table 4.

![FIGURE 1 Three-dimensional state-space model diagram of a petrochemical enterprise](image-url)
2. Construct Vector. Ecological carrying capacity indicators of the enterprise are divided into two categories. One is the positive indicators, pressure-bearing indicators, to reflect the development of enterprises. The other is the pressure indicators, calculated constructed vector, to reflect the pressure on the development of enterprises.

\[
ECS^*_i = ECS_i(\text{opr})ECC_i
\]  
(2)

Stress index \(ECS^*_i = ECC_i/ECS_i\)  
(3)

Pressure index \(ECS^*_i = ECS_i/ECC_i\)  
(4)

In this paper, we used both survey and interview to collect the relevant data of petrochemical enterprises in 2016. As a result, some ECC were depending on the local ecological system where the enterprise locates and the other were obtained through the clean production standard of petroleum refining industry released by the state environmental protection administration. ECS was obtained through the enterprise. Based on the collected data and the principle of the three-dimensional state-space model, we calculated ideal value and current value of eco-efficiency index of the petrochemical enterprise. The calculated results are shown in Table 5.

3. Calculated Results. We normalized the index weights in order to facilitate the calculation. The index weights are shown in Table 5. According to Table 5 and the previous formulas, we calculate the actual ecological carrying capacity of the petrochemical enterprise, which is the weighted distance \(D\) from the point on the surface to the origin in the three-dimensional state space.

\[
D = \sqrt{\sum_{i=1}^{n}(\omega_i \cdot ECS^*_i)^2} = 12.31
\]

The total ecological carrying capacity of the enterprise is

\[
ECC = \sqrt{\sum_{i=1}^{n}(\omega_i \cdot ECC^*_i)^2} = \sqrt{\sum_{i=1}^{n}\omega_i^2} = 11.98.
\]

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\]

4. Result analysis. Through in-depth analysis of the weight and ideal value shown in Table 5, we found that the indicators of phenol content, exhaust emissions, and loss rate of crude oil processing of the enterprise were higher and in an overloaded state. The treatment rate of industrial wastewater and industrial waste gas was 1, meaning at its full capacity. The amount of fresh water, unit of water consumption of crude oil, single discharge of industrial

| Two-level index judgment matrix | Economic total and benefit | Production technology and economy | Environmental pollution | Environmental management | Total resource | Resource utilization |
| --- | --- | --- | --- | --- | --- | --- |
| Economic total and benefit | 1 | 2.33 | 0.39 | 0.33 | 2 | 0.5 |
| Production technology and economy | 0.44 | 1 | 0.44 | 0.5 | 2 | 0.5 |
| Environmental pollution | 2.67 | 2.67 | 1 | 0.39 | 1.83 | 0.5 |
| Environmental management | 3 | 2 | 2.67 | 1 | 2 | 0.44 |
| Total resource | 0.5 | 0.5 | 0.94 | 0.5 | 1 | 0.39 |
| Resource utilization | 2 | 2 | 2 | 1.83 | 2.67 | 1 |

| Index weight table at all levels | Index type | State layer | Variable layer |
| --- | --- | --- | --- |
| Economics | Economic total and benefit (0.121) | Total assets (0.002) | Industrial output value (0.004) |
| | Production technology and economy (0.125) | Total profit (0.009) | Comprehensive commodity rate (0.002) |
| | Environmental pollution (0.177) | Crude oil processing loss rate (0.003) | Resource productivity (0.007) |
| | Environmental management (0.241) | Oil content in sewage (0.005) | Sulfide content in sewage (0.017) |
| | Resources (0.538) | Content of phenol in sewage (0.010) | Single displacement of industrial sewage (0.021) |
| | Resource utilization (0.266) | Exhaust emissions (0.008) | Treatment rate of industrial wastewater (0.041) |
| | Total resource (0.090) | Treatment rate of industrial waste gas (0.041) | Application amount of water (0.030) |
| | Unit primary oil consumption (0.044) | Application amount of Electrical energy (0.012) | Repetitive use rate of industrial water (0.018) |
| | Comprehensive energy consumption (0.081) | Application amount of steam (0.006) | Unit primary oil consumption (0.044) |
| | Environmental management (0.241) | Application amount of Electrical energy (0.012) | Repetitive use rate of industrial water (0.018) |
| | Resources (0.538) | Application amount of steam (0.006) | Unit primary oil consumption (0.044) |
| | Resource utilization (0.266) | Application amount of water (0.030) | Comprehensive energy consumption (0.081) |
wastewater, oil content in wastewater, sulfide content of sewage and other indicators were lower, at a loadable state. The actual ecological carrying capacity of the enterprise was 12.31, and the total ecological carrying capacity of the enterprise was 11.98. According to the basis of the ecological carrying capacity of petrochemical enterprises, we would see that the ecological carrying capacity of the enterprise was in an overloaded state.

5 | CONCLUSION

This study describes the interaction of economy, environment, and resources of the enterprise by applying the state-space model and the ecological carrying index model. Through the three axes of the state space, we can accurately describe the interactive relationship among economic development, resource utilization, and environment. The ecological carrying capacity of petrochemical enterprises was calculated by using the ecological carrying index model and the state-space model. The case analysis was done using an example of the enterprise to verify the feasibility and applicability of the three-dimensional state-space model applied to calculate ecological efficiency of the enterprise. Clearly, this application provides enterprises with theoretical tools to evaluate companies’ status of ecological efficiency. We make the following conclusions:

1. For the definition of eco-efficiency proposed by WBCSD, one important idea is to gradually reduce the impact of the entire life cycle of an enterprise on the environment and the intensity of consumptive resources to a level consistent with the ecological carrying capacity. Enterprise’s eco-efficiency has to reduce resources used, decrease energy intensity, reduce the emission of toxic substances, and maximize the use of renewable resources and other environmental resource. The three-dimensional state-space model constructed in this paper meets this connotation.

2. The three-dimensional state-space model describes petrochemical enterprises’ economic activities and the interactions with resources and the environment from the three aspects of resources, economy, and environment. In this three-dimensional geometric space, the petrochemical companies themselves act as pressurers on natural resources and the natural environment. The three axes of the state space represent the economic status of petrochemical enterprises, the use of resources, and the

### Table 5

| Index                                                    | Ideal value $ECC_i$ | Present value $ECS_i$ | State point $ECS^*_i$ |
|-----------------------------------------------------------|---------------------|-----------------------|-----------------------|
| Total assets (million Yuan)                               | 1 568 323           | 1 678 602             | 1.070                 |
| Industrial output value (million Yuan)                    | 4 214 230           | 3 081 505             | 1.368                 |
| Total profit (million Yuan)                               | 43 250              | 12 508                | 3.458                 |
| Comprehensive commodity rate (%)                          | 95                  | 93.97                 | 1.011                 |
| Crude oil processing loss rate (%)                        | 0.30                | 0.53                  | 1.767                 |
| Resource productivity (million Yuan/tons of crude oil)   | 1.25                | 0.48                  | 2.604                 |
| Oil content in sewage (kg/tons of crude oil)              | $3.5 \times 10^{-3}$| $8.5 \times 10^{-4}$  | 0.243                 |
| Sulfide content in sewage (kg/tons of crude oil)          | $1.79 \times 10^{-4}$| $3.0 \times 10^{-5}$  | 0.168                 |
| Content of phenol in sewage (kg/tons of crude oil)        | $1.77 \times 10^{-5}$| $3.4 \times 10^{-5}$  | 1.977                 |
| Single displacement of industrial sewage (tons of water/ tons of crude oil) | 0.50                | 0.35                  | 0.700                 |
| Exhaust emissions (tons)                                  | 455 600             | 647 123               | 1.420                 |
| Treatment rate of industrial waste water (%)              | 100                 | 100                   | 1.000                 |
| Treatment rate of industrial waste gas (%)                | 100                 | 100                   | 1.000                 |
| Application amount of water (million tons)                | 590                 | 373.25                | 0.633                 |
| Application amount of electrical energy (million kw-hr)   | 45 000              | 46320.05              | 1.029                 |
| Application amount of steam (million tons)                | 145.50              | 145.68                | 1.001                 |
| Repetitive use rate of industrial water (%)               | 99                  | 98.95                 | 1.001                 |
| Unit primary oil consumption (tons of water/tons of crude oil) | 0.80                | 0.58                  | 0.725                 |
| Comprehensive energy consumption (kg oil/tons of crude oil) | 60                  | 65.88                 | 1.098                 |
influence of the enterprises on the environment. This model can be used to describe the interaction between corporate economic activities and resources and the environment.

3. The results of the evaluation of ecological carrying capacity of petrochemical enterprises show that the most important factor affecting the eco-efficiency is the improvement of production technology of a company, especially the improvement of energy-saving technologies. The second importance is the management of production process or resources (improvements in the efficient use of water, raw materials, and energy). The third importance is to improve treatment technologies and management of pollutants (wastewater, waste residue, and exhaust gas).

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CONFLICT OF INTEREST

None declared.

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