Data-driven evaluation and optimization of the sustainable development of the logistics industry: case study of the Yangtze River Delta in China

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Abstract
In this study, a data-driven way is proposed to evaluate and optimize the sustainable development of the logistics industry (LI). Based on a comprehensive consideration of economic, societal, and environmental factors, an evaluation index system was established for the sustainable development of the logistics industry (LISD). Logistics industry-related data were collected from the Yangtze River Delta (YRD) from 2011 to 2020. The anti-entropy method was used to determine the index weight and process the data. Furthermore, the coupling harmonization degree and barrier degree models were used to analyze the coordinated development of each subsystem and identify key obstacles. Our results indicate that there are significant temporal and spatial differences in the level of LISD in YRD, with Shanghai (score 0.4834) being the best and Anhui (score 0.4553) the worst, showing a wave-like evolution in time. The coupling and coordination states among the subsystems are significantly different, with that of environmental benefits and other subsystems being poor. Moreover, innovation ability and environmental benefits are the main obstacle factors of this system. Based on the results of this study, targeted optimization countermeasures are put forward and evaluation indicators and research methods are suggested, which will provide the government and practitioners decision support, as well as provide theoretical and methodological support for LISD.

Keywords Sustainable development · Logistics industry · Coupling harmonization degree model · Obstacle factor · Yangtze River Delta · Data-driven

Introduction

Background

With the recent increase in serious energy and environmental problems, sustainable development has become a mutual development goal for all countries. The LI is a basic, strategic, and leading industry that sustains the economic development. It closely relates to agriculture and service industries, bridges production and consumption, involves a wide range of fields, and has a great developmental potential and a strong driving force.

However, logistics activities will inevitably consume many resources and cause pollution and threats to the environment while providing social and economic benefits. Both carbon emissions and energy consumption due to LI have been increasing annually. Excessive environmental pollution and resource consumption can easily restrict the development of logistics and affect economic and social progress (Cao 2018).
In the field of global sustainable development, research topics requiring urgent attention include how to (1) evaluate the level of LISD, (2) determine the coupling and coordination relationship between LI’s development and environmental protection and social responsibility, (3) identify and improve the obstacles of LISD, and (4) make targeted recommendations for government and practitioners and promote LI sustainable and healthy development.

Research summary

The concept of sustainable development was first put forward in the “World Conservation Program” in 1980. In subsequent studies, the theory has been continuously improved and has now become a strategic principle that is followed globally. Sustainable development mainly refers to the coordinated development of society, economy, population, and resources and environment and the overall development of human beings (Quesada-Mateo and Solís-Rivera 1990). The concept of LISD was proposed by Forster (1977), who believed that logistics activities would lead to environmental problems. Cooper (1991) mentioned the “green logistics” issue in “European Logistics” and thereafter, scholars began to pay attention to LISD. The research field of LISD mainly focuses on green low-carbon logistics, reverse logistics (Richnak and Gubova 2021), and the sustainable supply chain (Alarcon et al. 2021; Liu et al. 2021a, b, c, d; Kainuma and Tawara 2005). Research perspectives mainly include customer service (Lambert and Sharma 1990; Paddeu et al. 2017), logistics enterprise (Yan et al. 2011; Pandian and Abdul-Kader 2015), efficiency (Li et al. 2020; Mariano et al. 2017; Chen et al. 2016), and industry (Rezaei et al. 2018).

Based on the literature review methods reported by Tirkolaee et al. (2020, 2021), the literature review of LISD is divided into three aspects: the evaluation index system, evaluation methods, and optimization of LISD.

(1) Evaluation index system of LISD

Accurately evaluating the level of LISD based on evaluation results using appropriate methods to improve its efficiency is important. Yan et al. (2011) evaluated the sustainable development level of logistics enterprise from three perspectives: resource guarantee, sustainable state, and environmental impact. Li (2013) constructed an evaluation index system of LISD for logistics enterprises for industrial manufacturing from the perspective of input and output, considering economy, society, and environment. Mu et al. (2019) constructed an index system for the coordinated development of LI from four dimensions—economic environment, scale level, input level, and output effect of LI—and used the coupling coordination degree model to correlate the coupling and coordination of LI in Xinjiang.

Wang et al. (2020, 2021a, b) constructed an ecological efficiency evaluation model of logistics parks based on energy to quantitatively evaluate the sustainable development level of logistics parks. It can be seen that scholars mostly build evaluation index systems from the perspective of enterprises, etc., and further research is needed to establish an evaluation index system from an industrial perspective, taking into account the economy, society, and environment.

(2) Evaluation method of LISD

The evaluation methods of LISD are constantly improving, including AHP (Tonanont and Yimsiri 2009), data envelopment analysis method (Souza et al. 2010), structural equation model (Rao et al. 2010), case study method (Gargasas et al. 2019), and entropy weight method (Huang et al. 2019) which are considered useful. For example, Cao (2018) used DEA and Bayesian methods to evaluate the sustainable development efficiency of urban logistics industry by taking Jiangsu province in China as an example; Munch et al. (2021) used the expert evaluation method to evaluate the role of reverse logistics in the sustainable development of a food supply chain; Jiang et al. (2021) analyzed the impact of agricultural industrial clusters and the sustainable symbiotic development of LI using explanatory structural equations. The combination of these qualitative and quantitative research methods provides a good tool for the evaluation of the LISD; however, the data-driven evaluation methods based on data collection, processing, modeling, and application need to be further advanced (Liu et al. 2021a, b, c, d).

(3) Optimization of the level of the LISD

The optimization research on the level of LISD mostly focuses on policy recommendations. Based on their own research themes, scholars have proposed the establishment of an environmental protection assessment and supervision mechanism for the logistics industry, the implementation of precise environmental regulation policies (Dong et al. 2021), and the use of marketization; economical means to achieve carbon emission reduction (Long et al. 2020), encourage the integrated development of the secondary industry and the LI, improve energy efficiency, and formulate differentiated strategies (Bai et al. 2021) and other specific countermeasures to improve the level of LISD. Based on current literature, economic, social, and cultural backgrounds differ in different regions, and the path of LISD needs to be further improved in terms of pertinence.

Research limitations

Existing research represents a good foundation for the evaluation of the level of LI for sustainable development and
its development path. However, more intensive research is required.

1. Past research has mostly focused on analyses from the perspective of a single functional element or a single enterprise logistics model, such as transportation, distribution, reverse logistics, or green supply chain management. Research that considers the impact of logistics, economy, society, and environment on LISD as a whole requires further attention.

2. The evaluation indicators of the level of LISD are mostly selected from certain perspectives, such as low-carbon development and effectiveness. However, the comprehensiveness and accuracy of the indicators must be further explored, and the economy, society, and environment must be considered.

3. Scholars prefer evaluation methods, such as PCA and AHP, and further research is needed to determine how data can be used effectively and objectively. Compared with qualitative analysis and unclear evaluation, the data-driven evaluation system is based on comprehensive and multi-dimensional data, which can evaluate the level of LISD more objectively, which is helpful when clarifying the direction of LISD and enhancing the competitiveness of LI.

4. From the perspective of development countermeasures and suggestions, the existing research results mostly put forward countermeasures from a certain angle or the sustainable development direction of the entire LI, while the economic, social, and cultural backgrounds of different regions are relatively different. Further research on how to provide more targeted policy suggestions is required.

To address the above-mentioned difficulties, a data-driven evaluation and optimization method, which considers the economy, society, and environment comprehensively along with having an industrial perspective, is proposed in this study to quantitatively evaluate the LISD. The coupling coordination degree and obstacle degree models were employed to analyze the coordinated development, identify key obstacles, and propose corresponding optimization countermeasures to improve the level of LISD.

**Theoretical value and practical significance**

To address these research challenges, the studies of Huang et al. (2019) and Xiao (2020) were employed for reference and a data-driven sustainable development evaluation method as well as optimization countermeasures and suggestions for LI are proposed, which are of theoretical and practical significance.

The theoretical significance of this study can be summarized as follows: (1) a data-driven analysis is used to study the measurement, evaluation, and optimization of the level of LISD; an LISD evaluation index system is established and the level of the LISD is quantitatively evaluated to measure the capability of LISD from the aspects of economy, society, environment, and energy; (2) the coupling coordination degree and obstacle degree models of the LISD are established, and the mutual coupling mechanism and obstacle factors of the various subsystems of the LISD are revealed. Theoretical support for the ability to measure, evaluate, and optimize the LISD is provided, and its research foundation is enriched.

This study is practically significant in that it can aid the government and practitioners analyze the level of LISD from the perspectives of economy, society, environment, and energy with evaluating LISD and highlight the obstacles that affect it, in addition to identifying key factors and improving the level of LISD through a data-driven method.

**Manuscript structure**

In this study, three provinces and one city in YRD (Anhui province, Jiangsu province, Zhejiang province, and Shanghai) were considered and the anti-entropy method, coupling harmonization degree, and barrier degree model were used to explore the LISD. An evaluation index system was established for LISD. The level of LISD in YRD was determined by compiling and calculating basic data obtained from 2011 to 2020, the coordinated development degree between each subsystem was analyzed, and obstacles were identified. This manuscript is structured as follows: Data collection, processing, and modeling methods are introduced in the “Methods” section. In the “Case study” section, the three provinces and one city were used to evaluate the level of LISD, verify the effectiveness and feasibility of the method, and propose countermeasures. The conclusions are summarized in the “Conclusions” section.

**Methods**

The methodology used in this study aimed to assess LISD and identify obstacles more objectively, comprehensively, and accurately, and data collection, data modeling, and data analysis procedures, as well as applications, are introduced in this section.

**Process of method**

To improve the capability of LISD, we comprehensively and accurately evaluated it by exploring data-driven evaluation methods and optimization countermeasures for LISD from...
six perspectives: economic basis, development foundation, scale efficiency, innovation capability, environmental benefit, and social responsibility. First, relevant data from 2011 to 2022 regarding the LIs of the three provinces and one city in YRD were collected. Second, the min–max standardization method was used to process the original data in a dimensionless and standardized manner. Third, the anti-entropy way was used to determine the index weight. Subsequently, the comprehensive score of LISD was calculated based on the weight. Fourth, the coupling harmonization degree model was used to analyze the degree of coordinated development among various subsystems and the hinder degree model was employed to calculate the obstacle degrees of the first- and second-level indices. Finally, targeted optimization countermeasures and suggestions were identified. The methodological flowchart is shown in Fig. 1.

**Evaluation index system**

There is no special classification of LI in the current industrial system of various provinces in China, and the transport, warehouse, and postal industries account for more than 85% of the added value of LI (Long et al. 2020); therefore, data related to these are extracted to replace LI indicators. Based on previous research results and the principles of science, comprehensiveness, accuracy, and operability, an evaluation index system was constructed for the LISD. Subsequently, the level of LISD in the three provinces and one city in YRD (Anhui, Jiangsu, Zhejiang, and Shanghai) from 2011 to 2020 was calculated, as shown in Table 1.

Sample data were mainly obtained from the 2012–2021 China Statistical Yearbook, statistical yearbooks of various provinces and cities, China Energy Statistical Yearbook, and statistical bulletins of various provinces and cities. In order to eliminate the impact of price fluctuations, price-related variables such as GDP, value added of LI, internal R&D expenditures, and vehicle and vessel tax revenue were converted into actual values with 2011 as the base period.

For calculating the CO2 emissions of LI, we referred to a previous study by Sun et al. (2019) and the “2006 IPCC National Greenhouse Gas Inventory Guidelines” to calculate the carbon emission coefficients of the 17 types of energy involved, followed by determining energy consumption. The exhaust gas emissions of LI were calculated according to its various primary energy consumption pathways as in the energy balance sheets of the provinces and cities, including the emissions of SO2, NOX, PM2.5, and PM10. The exhaust gas emission was obtained by summation, and the emission coefficient was determined based on EPA, AP-42, and the Beijing emission coefficient (Sun et al. 2019; Li et al. 2018), combined with the actual development of China’s LI. Since the 2021 “China Energy Statistical Yearbook” has not yet been released, the least squares method was used for the missing energy data in 2020 to complete data prediction (Lin and Wang 2021).

Economic and development foundations provide crucial support for implementing LISD, and economies of scale can measure its output performance (Wang et al. 2019; Wang et al. 2021a, b). Technological innovation plays a leading role in LISD (Cao et al. 2020), environment effect is the impact of LISD on the environment, and social responsibility is the contribution to the country and the social security issues brought by LISD (Yang 2019). The evaluation index system comprehensively considers the economy, society, environment, and energy, and constructs an evaluation index system from six aspects: economic basis, development

| Data driven | Method flow | Research contents |
|-------------|-------------|-------------------|
| Data collection | Evaluation index system of logistics industry sustainable development | Data of sustainable development of logistics industry in Yangtze River Delta |
| Data processing | Min-max standardization, inverse entropy method | Weight of each secondary indicator, Comprehensive Horizontal Calculation |
| Data Modeling | Coupling coordination degree model, Obstacle degree model | Coupling coordination of subsystems, Obstacle degree of primary and secondary index |
| Analysis & practice | According to the above model data results | Suggestions on improving the sustainable development level of logistics industry |
**Table 1 Evaluation index system for LISD**

| Primary index (X<sub>i</sub>) | Secondary index | Direction | Reference |
|-----------------------------|----------------|----------|-----------|
| Economic basis (X<sub>1</sub>) | GDP (100 million yuan) X<sub>11</sub> | + | Dong et al. 2021 |
| GDP per capita (yuan) X<sub>12</sub> | + | Dong et al. 2021 |
| Market circulation scale (100 million yuan) X<sub>13</sub> | + | Dong et al. 2021 |
| Total foreign trade import and export (100 million $) X<sub>14</sub> | + | Dong et al. 2021 |
| Development foundation (X<sub>2</sub>) | Road network density in the built-up area (km/km<sup>2</sup>) X<sub>21</sub> | + | Bai et al. 2021 |
| Number of trucks (10,000) X<sub>22</sub> | + | Bai et al. 2021 |
| Number of employees (10,000) X<sub>23</sub> | + | Bai et al. 2021 |
| Fixed assets investments (100 million yuan) X<sub>24</sub> | + | Bai et al. 2021 |
| Scale benefit (X<sub>3</sub>) | Freight volume (10,000 tons) X<sub>31</sub> | + | Long et al. 2020 |
| Turnover of goods (100 million tons·km) X<sub>32</sub> | + | Long et al. 2020 |
| Added value of LI (100 million yuan) X<sub>33</sub> | + | Long et al. 2020 |
| Contribution rate of LI (%) X<sub>34</sub> | + | Long et al. 2020 |
| Innovation capacity (X<sub>4</sub>) | Information operation level (%) X<sub>41</sub> | + | Lin and Wang 2021 |
| R&D internal expenditure (100 million yuan) X<sub>42</sub> | + | Lin and Wang 2021 |
| Number of granted patent applications (items) X<sub>43</sub> | + | Lin and Wang 2021 |
| Number of undergraduate graduates (person) X<sub>44</sub> | + | Lin and Wang 2021 |
| Environmental effect (X<sub>5</sub>) | Energy consumption of LI (10,000 tons standard coal) X<sub>51</sub> | − | Li et al. 2018 |
| Electricity consumption of LI (billion kilowatt hours) X<sub>52</sub> | − | Li et al. 2018 |
| CO<sub>2</sub> emissions from LI (10,000 tons) X<sub>53</sub> | − | Li et al. 2018 |
| Exhaust gas emissions from LI (10,000 tons) X<sub>54</sub> | − | Li et al. 2018 |
| Social responsibility (X<sub>6</sub>) | Vehicle and vessel tax revenue (100 million yuan) X<sub>61</sub> | + | Wang, 2020 |
| Total wages of urban personnel (100 million yuan) X<sub>62</sub> | + | Wang, 2020 |
| Traffic accident fatalities (person) X<sub>63</sub> | − | Wang, 2020 |
| Traffic accident property damage (100 million yuan) X<sub>64</sub> | − | Wang, 2020 |

Data processing

**Data standardization method**

Original index data were standardized to eliminate unit restriction and transform it into dimensional index evaluation values, which are useful for the comparison and comprehensive evaluation of different indexes. Common standardization methods include min–max and z-score standardization. In this study, the min–max standardization method was used to standardize original index data. In addition, to avoid the meaninglessness of the logarithm, data translation was required. The specific calculation steps are as follows (Shi et al. 2020):

Positive target:

\[
X^*_y = \frac{X_y - \min\{X_y\}}{\max\{X_y\} - \min\{X_y\}} + 0.1, \quad i = 1, 2, \ldots, n; \quad j = 1, 2, \ldots, m
\]  

(1)

Negative target:

\[
X^*_y = \frac{\max\{X_y\} - X_y}{\max\{X_y\} - \min\{X_y\}} + 0.1, \quad i = 1, 2, \ldots, n; \quad j = 1, 2, \ldots, m
\]  

(2)

\(i\) is the first-level index code and \(j\) is the second-level index code. \(X_y\) represents the \(j\)th second-level index of the first-level index \(i\), such as \(X_1\) is the second-level indicator GDP of the first-level indicator economic basis, \(n\) is the number of first-level indicators, and \(m\) is the number of second-level indicators. In order to avoid the occurrence of 0 and 1 cases, leading to a deviation of the results, \(\max\{X_y\}\) is 1.01 times the median maximum value and \(\min\{X_y\}\) is 0.99 times the median minimum value and the values before and after normalization, respectively. \(X^*_y\) is the data after standardization and translation based on Eqs. (1) and (2).
Method used for the determination of index weight

Before scoring the entire system, each refined index must be weighted. The weight represents the degree of contribution of each of the indexes of the system. Therefore, selecting the appropriate method for the determination of index weight is important. Because the entropy weight method has high sensitivity to the different index degree, an extreme index weight is often obtained. In this study, the anti-entropy weight method was used to assign a weight to the index, which is less sensitive to the index difference degree. Based on this method, indicator failure can be avoided, the original data can be fully used to reduce interferences of indicators and subjective factors, and differences among indicators can be better reflected (Tomal 2021). The specific calculation steps are as below:

\[ p_j = -\sum_{i=1}^{n} h_{ij} \times \ln(1 - h_{ij}) \]  \hspace{1cm} (3)

In the Formula (3), \( h_{ij} = X_{ij}^*/\sum_{i=1}^{n} X_{ij}^* \)

\[ w_j = p_j / \sum_{j=1}^{m} p_j \]  \hspace{1cm} (4)

\( p_j \) is the anti-entropy value of the \( j \)th index and \( \omega_j \) is the weight of the \( j \)th index determined by the anti-entropy weight method.

Data model

The degree of interaction among the various subsystems within LISD can be quantitatively analyzed by the coupling coordination degree model, and the mutual coordination and cooperation between the systems and their evolution laws can be quantitatively characterized. The obstacle degree model can explore the key constraints in LISD, so that by identifying the coordination of subsystems and controlling and improving the key factors, the level of LISD can be effectively and rapidly improved, and targeted suggestions and countermeasures can be formed (Liu et al. 2020; Yang et al. 2021). The models are described below.

Calculations of comprehensive levels

Based on the weights determined by the above method and weighting method of multi-objective linear programming, the comprehensive level of LISD in three provinces and one city can be determined (Li et al. 2021):

\[ f_i = \sum (w_j \times X_{ij}^*) \]  \hspace{1cm} (5)

\( f_i \) is the comprehensive score of the level of the logistics industry for sustainable development in each province, \( X_{ij}^* \) is the standardized value of the \( j \)th second-level index, and \( \omega_j \) is the weight of the \( j \)th index. The same method can be used to count the comprehensive levels of various subsystems, such as economy basis, development foundation, scale benefit, innovation ability, environmental impact, and social responsibility.

Coupling grade model

Based on the comprehensive evaluation of subsystems, the coupling degree among the six subsystems can be calculated as follows (Liu et al. 2020; Guo and Deng 2019):

\[ C = \frac{6 \times \sqrt{X_1 X_2 X_3 X_4 X_5 X_6}}{X_1 + X_2 + X_3 + X_4 + X_5 + X_6} \]  \hspace{1cm} (6)

\( X_1, X_2, X_3, X_4, X_5, X_6 \) are the comprehensive levels of economic foundation, development foundation, scale benefit, innovation ability, environmental benefit, and social responsibility subsystem, respectively. The parameter \( C \) represents the degree of coupling and ranges from 0 to 1. The larger the value is, the better is the coupling among various subsystems within LISD and the greater is the degree of mutual influence among them.

Coupling harmonious grade model

Although the degree of coupling can be used to express the degree of mutual influence, it does not reflect the coordinated development degree among various subsystems. Therefore, the coupling and harmonious degree model was introduced to further determine the coupling and coordinated development levels among the various subsystems in LISD (Shi et al. 2020):

\[ D = \sqrt{C \times T}; T = aX_1 + bX_2 + cX_3 + dX_4 + eX_5 + fX_6 \]  \hspace{1cm} (7)

\( C \) is the coupling and \( T \) is the comprehensive evaluation index, which are used to reflect the overall level of subsystems; and \( a, b, c, d, e, f \) are the weight coefficients to be determined. In this study, all subsystems are considered to be equally important in LISD; therefore, \( a = b = c = d = e = f = 1/6 \). The parameter \( D \) is the coupling degree, with a value in the interval [0, 1]. The level is divided into ten degree, as shown in Table 2.

Obstacle degree model

The obstacle degree model was used to diagnose the obstacle factors of LISD in YRD more objectively by introducing three indicators: factor contribution degree (\( \omega_j \)), index
deviation degree \((1 - X_{ij}^*)\), and obstacle degree \((O_{ij})\). The obstacle degree was calculated as shown in Eqs. (8) and (9) (Yang et al. 2021; Wang and Dong 2019):

\[
O_{ij} = \frac{\left(1 - X_{ij}^*\right) \times \omega_j \times 100\%}{\sum\left(1 - X_{ij}^*\right) \times \omega_j}
\]

\[
O_i = \sum O_{ij}
\]

where \(i\) is the first-level index code and \(j\) is the second-level index code. \(X_{ij}^*\) is the standardized value of the \(j\)th second-level index, \(1 - X_{ij}^*\) represents the degree of deviation of the index, and \(\omega_j\) is the weight of the \(j\)th index (Wu et al. 2021). \(O_{ij}\) is the obstacle degree of the \(j\)th second-level index of the first-level index \(i\) for sustainable development and \(O_i\) represents the obstacle degree of the first-level index.

### Data application

This research is based on a data-driven evaluation and optimization of the logistics industry sustainable development. By collecting the relevant data of LISD, the models of coupling coordination and obstacle degrees were used to optimize the LISD. Specific data applications are as follows:

First, combined with connotation of LISD, build a list database of LISD, extract the indicators of LISD from it, then considering relevant literature and the economy, society, and the environment, an index system was constructed that can be used to evaluate the level of LISD comprehensively and accurately.

Second, the level of LISD was evaluated. The anti-entropy weight method was used to count the weight of each indicator, which reflects the importance of the indicator and can be used to calculate the comprehensive score of level of LISD and the scores of each subsystem. The system score better reflects the level of LISD of each province and city as well as the advantages and disadvantages.

Third, the degree of the coordinated development and obstacles of every subsystem were analyzed. The capability of LISD is closely related to the coordinated development of various subsystems and the identification of obstacles. The coupling degree model can be used to measure the degree of the coordinated development of each subsystem. The obstacle degree model can be used to effectively identify key obstacles based on the obstacle degree and guide sustainable development.

Fourth, suggestions were made regarding the LISD. Based on the results of the data analysis, a sustainable development path was proposed for the LIS in YRD: promote the scale benefit, strengthen social security awareness, enhance social responsibility, enhance innovation capabilities, and drive sustainable development on the basis of green and low carbon. The data application is shown in Fig. 2.

![Fig. 2 Data application](image_url)
Case study

The above-mentioned methods were applied to three provinces and one city in YRD. We discussed the applicability of the total system of LISD in these regions, comprehensive level of each subsystem, and obstacle factors. Subsequently, countermeasures and management procedures are suggested, which can be implemented to modify LISD.

Case study background

YRD is on the eastern coast of China. The YRD city cluster is one of the six world-class city clusters that are recognized internationally, including Anhui, Jiangsu, and Zhejiang provinces and Shanghai, with a regional area of 358,000 km². In 2019, the total freight volume of YRD urban agglomeration reached 6.026 billion t, the freight turnover was 401.6 billion t/km, and the LI achieved an added value of 590.166 billion yuan. Logistics demand is relatively high and has become an important force in promoting economic development. In April 2020, the National Development and Reform Commission and the Ministry of Transport issued the “Higher Quality Integrated Development Plan for Transportation in the Chang Jiang Delta,” which emphasized the need to improve integrated transportation service capabilities and the efficiency of urban and rural logistics distribution. As an important regional economic growth pole of the country, LISD will support the realization of the integrated development of YRD. This study considers the research on the LISD in YRD as a starting point and surveys and analyzes the measurement, evaluation, and optimization of the level of LISD in this region to identify the shortcomings and obstacles for promoting the level of LISD in YRD, and the national LI.

Data processing results

Equations (1) and (2) were used to standardize the original data and Eqs. (3) and (4) were used to calculate the weight of each index. The results are depicted in Fig. 3.
According to Fig. 3, the indexes amount of patent authorization, volume of goods turnover, number of trucks, added value of LI, and carbon dioxide and exhaust emissions have large weights, which also highlights the key points that should be focused on for LISD.

Based on Eq. (5), the comprehensive score of LISD level in YRD was calculated. The results are represented in Table 3, Fig. 4, and Fig. 5.

As shown in Fig. 4, since 2011, the level of LISD in the YRD region has shown a steady upward trend. The comprehensive level was only 0.2906 in 2011, and after 10 years of rapid development and effective allocation, it increased to 0.6893 in 2020. The decline in the comprehensive level of YRD region in 2015 compared with the level in 2014 is mainly attributed to the promotion of the “camp reform” tax system in all industries in China in 2015. The logistics expenses in that year increased to 2,048.4 billion US dollars, higher than that in other years. The decline in transportation volume and profits inhibited the development of the regional LI in the YRD region, which led to a decrease in the comprehensive level in 2015 compared with that in 2014.

From the perspective of each subsystem, development foundation contributes the most to the improvement of the comprehensive level, and all provinces and cities in YRD attach great importance to the input of human, financial, and material resources in the LI. However, environmental effects not only did not contribute to the improvement of the comprehensive level, but also played a restraining role. The degree of environmental impact has been declining annually in the past 10 years, especially in 2017, which showed the largest decline compared with that in 2016. This is mainly because the state has formulated a series of policies to encourage the development of the LI, such as increasing tax reduction and clearing efforts. The YRD region has taken this opportunity to increase its investment in the LI, and the corresponding output has also greatly increased. As most of the vehicles used are energy-intensive, the energy consumption and CO₂ and waste gas emissions of the LI are greatly increased. The changing trend of other subsystems is basically the same as that of the total system, and their contribution to the total system is equal. It can be seen that improving the development level of environmental benefits should be the key direction of the LI in the YRD region.

Table 3 and Fig. 5 show that since 2011, the comprehensive level of LISD in the three provinces and one city is basically consistent with the regional trend of YRD, both of which are rising steadily. Except for that in Shanghai, the comprehensive level of the other three provinces in 2015 was lower than that in 2014. This is because the tax policy of “camp reform” did not have an impact on Shanghai, and vigorous investments in fixed assets and enhancements in innovation ability occurred with the rising expenses of LI. Jiangsu province was at the highest level from 2011 to 2015, which was replaced by Shanghai after 2015. From 2011 to 2017, the comprehensive level of LISD in Anhui province was the lowest, but in 2018, it surpassed Shanghai and Jiangsu province due to the national integration strategy of YRD. Since 2018, Anhui cities have been brought into the YRD continuously, which was conducive to a broad development space. In 2020, the comprehensive level of LISD in Anhui province surpassed than in other provinces and cities and reached the highest level.

The scores calculated in this study can only evaluate the level of LISD as a whole, but cannot enable the understanding of the interaction among subsystems and the overall coordinated development level of the system. Therefore, the coupling coordination degree model was used according to Eqs. (6) and (7), and the data presented in Fig. 5 were used to calculate the coupling coordination relationship among subsystems of LISD in three provinces and one city in YRD. The specific results are shown in Table 4 and Fig. 6.

Based on the information in Table 4 and Fig. 6, we can see that the coupling degree of each subsystem of LISD in the YRD region is greater than 0.7 in all years except 2011, and greater than 0.9 in 4 years, which shows that there is a good coupling relationship within the system. However, as the coupling coordination degree increased annually, the system became imbalanced, which can be represented in two stages: the first stage is 2011, in which the coupling coordination level is considerably maladjusted, and the development of subsystems is seriously unbalanced. During this, the LI only pursued economies of scale, and extensive development did not consider the impact on the environment; the second stage is 2012–2015, which is a stage of moderate disorder. During this period, the LI in YRD changed from traditional to modern, and the level of management and technology application improved; thus, the coupling and coordination relationship became moderately imbalanced. Since 2016, the coupling and coordination relationship has increased greatly, but it remains in a state of moderate disorder and has not entered the coordination stage, which shows that there are still many
problems of LISD in the YRD region. This is primarily due to the lack of high-quality logistics services, and there are considerable requirements for the LI in YRD to be coordinated and orderly.

The coupling degree of the three provinces and one city is mostly above 0.8. Except for Jiangsu province, all other provinces and cities show a positive trend of transition from high to low imbalance, which indicates that the subsystems of LISD are developing in a coordinated and orderly manner, but they are still not fully coordinated. All provinces and cities should pay attention to the coordination of economy, society, energy, and environment. In 2019 and 2020, Shanghai changed from low to moderate imbalance, mainly because the number of traffic accident deaths in 2019 nearly doubled that in 2018; thus, significant attention should be paid to the social security problems brought by the LI. The coupling coordination degree of Jiangsu province shows an upward-downward trend with 2014 as the node, indicating that the LI needs an improved development path. Zhejiang and Anhui provinces can continue their current development direction and policies to finally achieve coordinated development.

Following this, we analyzed the pairwise coupling among each subsystem, as shown in Fig. 7 and Fig. 8.

Figure 7 shows that the coupling coordination degrees in other subsystems in YRD had a steady upward trend, with
the exception of the environmental benefits and other sub-systems that decreases annually, but the declining rate slows down and the prospect is promising. The coupling coordination degrees of economic base and scale benefit, economic base and social responsibility, and development base and scale benefit in 2020 were lower than those in 2019, which could be due to the impact of the COVID-19 epidemic in 2020, which reduced the economic growth and transportation volume.

As shown in Fig. 8, the coupling coordination degree among subsystems in Shanghai is improving, with that between the development foundation and social responsibility being the highest, and that between innovation ability and environmental benefit being the lowest. Jiangsu province has the highest coupling coordination degree between development foundation and scale benefit, and the lowest between innovation ability and environmental benefit. This indicates that Shanghai and Jiangsu province should enhance their innovation ability and pay attention to environment protection in the future. Zhejiang province and Anhui province have the highest coupling coordination degree between scale benefit and social responsibility, while the lowest between economic base and environmental benefit. It is clear that these provinces should strengthen their environment protection along with developing their economies and fulfilling social responsibility.

Moreover, according to the standard values calculated by Eqs. (1) and (2), the obstacle degree of each index was calculated using the obstacle degree model and Eqs. (8) and (9), and the obstacle factors of LISD in three provinces and one city in YRD were identified in order to further clarify the direction for improvement of LISD. The results obtained are shown in Table 4 and Figs. 9 and 10. Given the space constraints, only the top two obstacles of first-level indicators and the top five obstacles of second-level indicators are listed.

From Fig. 9, it can be seen that the obstacle degree of scale and environmental benefits is increasing annually, especially environmental benefit, which shows that improving the environmental benefit is critical for LISD in YRD. As shown in Fig. 10, the main obstacle systems for LISD in the YRD region are environmental benefit, scale benefit, and innovation ability, with obstacle degrees of 21.17, 18.39, and 18.13%, respectively. The main obstacles to the sustainable development of Shanghai’s LI are innovation ability and scale benefit, with obstacle degrees of 21.34 and 21.19%, respectively. The main obstacle factors for LISD in Jiangsu province are innovation ability and environmental benefits, with obstacle degrees of 21.28 and 20.16%, respectively. The principal obstacle factors for the sustainable development of LI in Zhejiang and Anhui provinces are environmental and scale benefits, with obstacle degrees of 22.69 and 25.25 (environmental) and 18.54 and 16.76% (scale), respectively.
Among all the obstacle systems, the highest frequency (five) is that of scale benefit, followed by environmental benefit (three) and innovation ability (two).

As shown in Table 5, among all the obstacle indicators, the highest frequency (four) is for energy consumption, followed by patent authorization and \( \text{CO}_2 \) emissions (three each), and lastly number of trucks, cargo transportation, and traffic accident deaths (two each). The three provinces and one city have their own characteristic industries and development paths, with differing obstacle factors. Due to the relatively large proportion of traditional industries, such as iron and steel, cement, smelting, and coal, which are important in the country’s industrial sector, the high energy consumption per unit of logistics output has become a major obstacle in the Anhui province. In addition, the logistics in the Anhui province were developed late compared with that in other provinces and cities. Energy consumption and carbon dioxide and waste gas emissions are the main obstacles in this area.

Shanghai and Jiangsu province have attached great importance to the development of new energy and materials since the 12th Five-Year Plan, and the environmental benefits are positive, but the innovation ability and infrastructure construction aspects need to be strengthened. The advantageous industries in Zhejiang province are mainly concentrated in textiles, waste products, and software and service, which need to be strengthened in terms of environmental protection and economic development.

**Policy suggestions**

On the base of above-mentioned analysis, the below suggestions are proposed in this study to modify the LISD.

**Speed up the promotion of scale benefit based on green and low-carbon development**

From our analysis in this study, it can be seen that the environmental problems caused by LI in the YRD region are one of the main factors restricting the LISD, and scale benefit is another main obstacle of the system. Therefore, YRD should strengthen the management of environmental impact of the LI and promote scale benefit based on the improvement of environmental benefits to promote the coordinated development of the two factors. This can start by changing the energy consumption pattern, reducing the total energy consumption, improving the energy utilization rate (the obstacle degree of energy consumption ranks second), and encouraging logistics enterprises to increase investment in energy-efficient and new energy trucks and other equipment through tax relief, amortization of depreciated assets, and financial support. Shanghai’s environmental benefit score is the highest (0.0887), which shows that the region pays more attention to environmental governance, and takes measures to reduce environmental pollution caused by LI. In addition, from the proportion of \( \text{CO}_2 \) and waste gas emissions of LI to energy consumption, it can be seen that Shanghai’s environmental benefit is obviously higher than that of the other three provinces. Jiangsu, Zhejiang, and Anhui can learn and adapt the energy utilization mode of Shanghai’s LI. Shanghai should continue to play the role of the core city, playing a vital role in the technical, economical, and logistical demand of the other three provinces, so as to promote the green and low-carbon development of the LI in YRD and lead to its integration as soon as possible.

**Table 5** The top 5 obstacles of secondary indicators

| Area   | Barrier indicator                                                                 |
|--------|-----------------------------------------------------------------------------------|
| YRD    | Number of patents granted, energy consumption, exhaust emissions, \( \text{CO}_2 \) emissions, cargo transportation |
| Shanghai | Number of patents granted, volume of goods transported, number of undergraduate graduates, GDP per capita, number of trucks |
| Jiangsu | Number of patents granted, contribution rate of logistics industry, number of employees, energy consumption, traffic accident fatalities |
| Zhejiang | Energy consumption, cargo transportation, total foreign trade import and export, \( \text{CO}_2 \) emissions, number of employees |
| Anhui   | Exhaust emissions, energy consumption, \( \text{CO}_2 \) emissions, traffic fatalities, number of trucks |
Strengthen social security awareness and promote social responsibility

The obstacle degree of traffic accident fatalities is 4.41%, which has become the main factor hindering the coupling and coordination of Shanghai’s LI in 2019 and 2020. Therefore, the LI in YRD should strengthen the awareness of social security. There will be hidden dangers of accidents in every link of LI, especially regarding transportation, which is among the key factors of accidents. Various sensors can be installed on trucks, and the generated data can be collected into the on-board chips and clouds, so that the road traffic can be perceived; the driver’s state can be identified; fatigue-associated symptoms, such as eyes closed and yawning, can be detected; and dangerous driving behaviors, such as mobile phone distractions, can automatically trigger to make sound intervention. If the warning is invalid, it can be reported, and the safety operators can intervene manually until the danger is relieved. Reducing the occurrence of traffic accidents is an effective way to improve the level of LISD.

Enhance the innovation ability for driving sustainable development

In the system of LISD in YRD, the innovation capability system score is the lowest (0.0735), and the degree of patent authorization index obstacle ranks first in YRD in Shanghai and Jiangsu provinces, while the coupling coordination degree with other subsystems is almost at the bottom. Therefore, the YRD region should strengthen the investment and application of logistics scientific and technological achievements, while also improving the logistics infrastructure construction, strengthening the tightness of logistics information networks among cities, increasing the internal expenditure of R&D, and creating a good environment for logistics innovation and development. Cities with a higher innovation and development level should take the lead in guiding cities with a lower development level, and actively direct the flow of innovation elements among cities with different development levels. On the other hand, we should train and introduce innovative talents to form a scientific and technological innovation mechanism with clear innovation elements gathering and transformation pathways. Through the spillover effect of knowledge and technology, we can narrow the gap between the Anhui province and other provinces and cities and promote the integration of the YRD.

The YRD is one of the regions with the most active economic development, the highest degree of openness, and the strongest innovation capability in China, and it has an important strategic position in the overall situation of the country’s modernization drive. The policy recommendations on the LISD in the YRD can be used for reference by other regions. In the future, the effectiveness of the policy recommendations can be studied in other regions to provide reference for the LISD across the country and the world.

Discussion and management insights

This study has the following advantages over previous work (Wang et al. 2020, 2021a, b). First, the data-driven evaluation index system in this study can analyze the level of LISD, clearly quantify it, and provide theoretical support for evaluating the ability of LISD. Second, the data-driven coupling coordination degree and obstacle degree models can analyze the relationships among all subsystems of the LI and aid sustainable development. From the perspective of correlation, we can observe the logistics system and provide it with optimal decision-making methods. On the basis of green and low carbon, the level of LISD can be improved by increasing the investment of LI, enhancing its innovation ability, and strengthening social security awareness. Finally, based on data-driven methods, an effective tool for evaluating and optimizing the level of LISD was developed which can provide targeted optimization suggestions for LISD in the YRD region, for reference in other regions, and a reference for choosing the development direction of regional LI as well as promoting sustainable development.

Based on our results, the following management insights can be summarized:

First, the government and major enterprises have been trying to improve the level of LISD; however, using a relevant data-driven system can quickly improve the level of LISD.

Second, the experience of LISD in YRD can be used for reference by other regions; green and low-carbon development is the inevitable requirement of LISD, with promotion of innovation ability being its driving factor and fulfillment of social responsibility being its realistic mission. Thus, improving the scale benefit of the LI should be the pathway of LISD. This optimization decision is the key to improve the level of LISD.

Third, the system of LISD is a complex ecosystem, involving related subsystems, such as economy, society, and environment. The interaction among internal subsystems affects the level of LISD, so it is necessary to identify, analyze, and optimize each subsystem as much as possible on the basis of quantitative evaluation of the level of LISD.
Conclusions

Sustainable development is a common goal of the global logistics industry. LISD is inevitable for global economic and social development and is essential for environmental protection and resource conservation. This study is based on data-driven research on the evaluation and optimization methods for LISD. Our main findings are as follows: (1) an evaluation index system was constructed for LISD. The index system comprehensively considers economy, society, and environment, and its indicators are more comprehensive and precise; (2) the coupling harmonization degree and barrier grade models were used to analyze the coordinated development level of various subsystems and identify obstacles of LISD more objectively and scientifically; and (3) policy recommendations were put forward based on data-driven sustainable development optimization of the LI and basic, service, innovation, and low-carbon subsystems and identify obstacles of LISD more objectively and scientifically; and (3) policy recommendations were put forward based on data-driven sustainable development optimization of the LI and basic, service, innovation, and low-carbon aspects, providing the government a theoretical basis to guide the development of the LI and assist practitioners.

The evaluation of LISD is a complex systematic process and encompasses a wide field of research. In future research, the integrity and accuracy of the evaluation index system for the level of LISD will be further explored and the data will be expanded, adding more provinces and years for dynamic comparison and analysis. Obstacles to LISD will be analyzed more systematically and increasingly effective suggestions for LISD will be put forward.

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Declarations

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