Journal of Systems Science and Information
Aug., 2023, Vol. 11, No. 4, pp. 488–502
DOI: 10.21078/JSSI-E2022105

Industrial Pollution Governance in Beijing-Tianjin-Hebei Based on Industrial Relocation

Yuan ZENG
School of Economics and Management, University of Chinese Academy of Sciences, Beijing 100190, *China*
E-mail: 2522952984@*qq.com*

Meng WANG*
School of Economics and Management, Beijing University of Chemical Technology, Beijing 100029, *China*
E-mail: 17312878737@163.*com*

Qianqian ZHANG
School of Economics and Management, Beijing University of Chemical Technology, Beijing 100029, *China*
*E-mail: m*17862730334@163.*com*

Lijuan DING
School of Economics and Management, Beijing University of Chemical Technology, Beijing 100029, *China*
*E-mail: dinglijuan*01@126.*com*

Jun WU
School of Economics and Management, Beijing University of Chemical Technology, Beijing 100029, *China*
E-mail: wujun@mail.buct.edu.cn

Ernesto D.R. SANTIBANEZ GONZALEZ
Industrial Engineering Department, Faculty of Engineering, Universidad de Talca, 74104, *Chile*
E-mail: santibanez.ernesto@gmail.com

Abstract Industrial relocation and ecological subsidy are viewed as effective ways to overcome transboundary industrial pollution. In this paper, we study the transboundary industrial pollution control problem in the Beijing-Tianjin-Hebei region in the context of industrial relocation. Firstly, we construct an economic model of pollution control with relevant variables such as environmental tax and environmental damage coefficient. Secondly, we solve the economic contributions by using the proportional split-off solution. Finally, we compare the optimal relocation quantity and welfare functions

Received December 14, 2022, accepted May 5, 2023
Supported by Foreign Expert's Program of Ministry of Science and Technology of China (G2022106001L)
*Corresponding author

in both cooperative and non-cooperative cases. Our research finds that: 1) The optimal strategy is closely related to utility coefficient, environmental loss coefficient and incentive intensity coefficient. 2) The welfare function and the optimal relocation quantity in the cooperative case are significantly greater than those in the non-cooperative case. Based on the analysis, some suggestions are provided for transboundary industrial pollution management.

Keywords Beijing-Tianjin-Hebei region; industrial relocation; ecological subsidy; welfare function; the proportional split-off solution

1 Introduction

It is well-known that transboundary industrial pollution problems seriously threaten the survival and development of our society and become a hot issue in the world. The Chinese government has always been concerned about environmental governance and considered environmental protection as one of its major national strategies. The Beijing-Tianjin-Hebei region is one of the most representative regions, where economic, social and environment are highly correlated. As the capital of China, Beijing is facing critical environmental challenges, and some effective measures are urgently needed. Industrial relocation is regarded as an efficient way to alleviate environmental pressure[1]. Since 2015, the Chinese government has shifted some low-end, inefficient and low value-added economic industries from Beijing to Tianjin and Hebei, and has formulated relevant policies to promote environmental management in the Beijing-Tianjin-Hebei region[2]. During the same year, the Political Bureau of the Central Committee of the Communist Party of China (CPC) adopted the Outline of the Beijing-Tianjin-Hebei Synergistic Development Plan[3]. On September 12, 2021, the General Office of the State Council issued the Opinions on Deepening the Reform of the Ecological Protection Subsidy System.

1.1 Research Methodology and Scope of the Study

Our paper is closely related to three streams of literature. The first stream of literature is on the problem of industrial relocation, the second stream investigates the problem of pollution control, and the last studies the regional ecological compensation mechanism.

Many scholars had conducted useful analysises and explorations on the issue of industrial relocation. Chen, et al.[4] used the spatial Durbin model (SDM) to examine the temporal characteristics of the regional industrial land utilization efficiency and the spatial characteristics of the provincial industrial relocation. Wang, et al.[5] integrated multi-regional input-output analysis and barycenter model to investigate the hidden impacts. Yuan, et al.[6] thought ecologicalization of the industrial structure has the greatest influence on economic growth in terms of the relationship between industrial structure and economic growth in the Beijing-Tianjin-Hebei region. Lin, et al.[7] deepened the understanding of the environmental effects of industrial relocation. The low development level of transfer-out and transfer-in region both resulted in the downgrading environmental performance with firm relocation[8].

Although industrial relocation can optimize the industrial structure and layout of the whole region to a certain extent, the negative impact can't be ignored. Jiang and Lyu[9] analyzed provincial panel data from 2003 to 2016 to study the impact of environmental regulation on pollution-intensive industry relocation. Liu, et al.[10] used three classic kinds of cost-sharing methods to allocate the cost of air pollution governance. Yang, et al.[11] found developed provinces transfer carbon emissions to less developed provinces through inter-provincial trading, and this game would result in the problem of unequal responsibility for carbon dioxide emissions reduction between regions.

Wang, et al.[12] concluded that the joint air pollution control strategy should take various factors into account, such as the cost-effectiveness and the difficulty of collaboration between the cities involved. Xu, et al.[13] developed a tripartite evolutionary game model introducing prospect theory and validated numerical examples with a system dynamics approach. Wang, et al.[14] analyzed the cooperation mechanism from the perspective of institutional collective action (ICA) theory and evaluated the policy effects of cooperative pollution control and governance in the Yangtze River Delta region. Wang, et al.[15] used the 3SLS estimation method to study the relationship between air pollution and economic growth. Zhang, et al.[16] proposed the new concept of proportional split-off solution into the cooperative game model, taking the Yangtze River Delta region as an example, to analyze the economic marginal contribution of each city in the region. The huge volume of environmental monitoring data, which has reasonable real-time performance, provides strong support for in-depth analysis of air pollution characteristics and causes[17]. Luo, et al.[18] employed ensemble Kalman filtering (EnKF) to evaluate the changes in major air pollutant emissions region. Lin, et al.[19] studied that increasing the carbon tax rate in a lower range can promote the emission reduction level and emission reduction amount under centralized decision.

Some scholars consider ecological subsidy can promote environmental collaborative governance. Yang, et al.[20] studied the calculation of ecological subsidy involved in the pollution control process in the Beijing-Tianjin-Hebei region and the interested stakeholder problems. Zheng, et al.[21] explored the influence of ecological compensation mechanism on industrial structure upgrading based on multi-stage construction of the dynamic DID model. Wang, et al.[22] proposed that the ecological subsidy mechanism is an effective economic policy to resolve resource conflicts, enhance overall interests and achieve environmental sustainability. Ling, et al.[23] constructed a game model of optimal control of transboundary pollution in two adjacent areas composed of the acceptance area and the compensation area. Wang, et al.[24] proposed that government subsidies to supply chain members could improve the level of carbon emission reduction by constructing differential game models.

1.2 Contributions of This Paper

The previous research on the ecological subsidy mechanism is mainly limited to the one-way compensation, and less research is conducted from the perspective of multiple subsidy mechanism between the central government and local governments.

The proportional split-off solution can calculate the respective economic contribution rate of allied members from a system perspective, and can provide an effective method to allocate benefits in alliance. However, this method is seldom used for the cooperative pollution management.

Comparing the existing literature, the main contributions of this paper are as follows:

We study the pollution governance in the Beijing-Tianjin-Hebei region in the context of industrial relocation, the research object covers all members of Beijing-Tianjin-Hebei, making the research perspective more macroscopic. In addition, this paper establishes subsidy mechanism with the central government and local governments, which makes the study more comprehensive and specific.

We consider the economic statistics and economic contributions of the Beijing-Tianjin-Hebei region, introduce the proportional split-off solution model and cooperative game approach to the study of pollution management under the ecological subsidy mechanism, and analyze the characteristics of "benefit sharing", "collaborative management" and "cost construction" in the process of pollution management by setting different parameters for simulation, so that the model can better reflect the long-term and dynamic industries change and development trends.

We find that existing studies have applied the methods of cooperative game, benefit sharing to the field of environmental pollution governance, and have studied various aspects such as regional industrial relocation, regional ecological subsidy and synergistic governance mechanism issues, which provided theoretical reference and methodological guidance for our paper to study Beijing-Tianjin-Hebei regional pollution governance. Although valuable conclusions have been found by the above studies, some shortcomings still exist. As in Table 1, We find that the studies of Chinese scholars focus on environmental governance but have certain limitations on the cost and welfare sharing of collaborative management.

Table 1 The main difference between our research and previous research

paper	industrial relocation	collaborative governance	ecological subsidy
Li, et al.[2]	✓		
Wang, et al.[5]	✓		
Wang, et al.[14]		✓	
Li, et al.[2]		✓	
Wang, et al.[12]		✓	
Zheng, et al.[21]			✓
Wang, et al.[22]			✓
Yang, et al.[20]	✓		✓
Our paper	✓	✓	✓

1.3 Organization of the Paper

The paper is organized as follows. Section 2 firstly introduces the basic model, constructing the welfare function in the case of cooperation and non-cooperation. Secondly, it uses the proportional split-off solution to reasonably allocate the cooperative benefits among Beijing, Tianjin and Hebei. Finally, it analyzes the welfare model to derive the optimal relocation quantity and revenue. Section 3 sets numerical parameters for the welfare model and conducts numerical simulation analysis. Section 4 puts forward targeted suggestions and recommendations based on the numerical analysis.

2 Modeling

2.1 Problem Description

Industrial relocation of Beijing, Tianjin and Hebei is an effective means to decongest Beijing's non-capital functions, while comprehensively promoting the integrated development and forming a pattern with reasonable spatial layout. Beijing relies on the advantages of science and technology and human resources to become a science and technology innovation center, undertaking industrial research and development, design, services and other functions in the Beijing-Tianjin-Hebei region, while Hebei and Tianjin areas around energy conservation and environmental protection, medicine, furniture, leather and other industries to form a number of special bases[25].

We consider the industrial relocation of the Beijing-Tianjin-Hebei region under the jurisdiction of the central government. The receiving city carries out pollution governance activities through more investment and ecological maintenance to reduce energy consumption and pollution emissions in the production process. Based on "the polluter pays principle", the transfer-out region subsidizes for the receiving city according to undertaking quantity, and helps it to curb environmental pollution. At the same time, the central government, in order to better promote the implementation of the industrial relocation policy in the Beijing-Tianjin-Hebei region and stimulate the intrinsic motivation of inter-governmental pollution governance, subsidizes the certain development opportunities and the ecological investment.

2.2 Assumption

Assumption 1 Assuming that the production quantity Q and pollution emissions q of industrial enterprises in the jurisdiction of neighboring regions are linearly related in finite time, namely, $Q = Q(q)$, the region can generate a certain payoff $R(Q)$ through industrial production. Specifically, the payoff function can be characterized by the pollution emissions q, and it is a quadratic increasing convex function with respect to q. Drawing on Jørgensen, et al.[26] and Breton, et al.[27], the payoff function is as follows:

$$R(Q) = a_i q - \frac{q^2}{2}, \quad i = 1, 2, 3, \tag{1}$$

where a_i denotes utility coefficient of industrial production, $i = 1, 2, 3$ represent Beijing, Hebei and Tianjin, respectively. $a_1 > a_3 > a_2 > 0$. The payoff function increases with a_i.

Assumption 2 Assuming that the economic level of the transfer-out region is higher than that of the receiving city and has higher environmental requirements. To promote the active implementation of this policy, the subsidy mechanism is set up to provide them with certain compensation according to the receiving quantity. The proportional coefficient of subsidy is β, which satisfies $\beta \geq 0$. The central government imposes tax on the pollution produced by industrial production with tax factor of p.

Assumption 3 Region i decides its pollution control and emission reduction efforts according to the number of pollutants in the jurisdiction θ_i, assuming that θ_i is linearly related to the quantity of regional pollution, $\theta_i = kq_i$; Regarding the setting of pollution control investment cost, the actual pollution control and emission reduction cost of region i is characterized by $\frac{g\theta_i^2}{2}$, and $g > 0$ is the investment cost coefficient of pollution control[28].

Assumption 4 Assuming that the diffusion of pollutants through natural media will cause environmental damage to another region. $d_i^j q_i$ represents the environmental damage caused by the diffusion of q_i to region j, and d_i^j represents the diffusion coefficient of pollution emission damage[29]. In addition, the environmental loss coefficient d represents the damage degree of pollution emission to the local environment. According to the theory of Poyago-Theotoky[30], the quadratic of total pollution emissions represents environmental loss, that is, $W(q) = \frac{1}{2}dq^2$. The parameter settings in the hypothesis are shown in Table 2.

Table 2 Decision variables and parameters

Parameters	Description
θ_i	Mitigation effort: Quantity of environmental governance of region i
β_1	Beijing's incentive intensity coefficient for other region
p	Unit environmental tax price
β_2	The central government's incentive intensity coefficient for transfer-out region
q_i	Emission quantity of region i
β_3	The central government's incentive intensity coefficient for the receiving city
a_i	Utility coefficient of industrial production of region i
m	The quantity of industrial relocation
g	Cost coefficient of mitigation effort
d	Environmental loss coefficient of local emissions
k	Marginal impact coefficient of mitigation effort
d_i^j	Environmental loss coefficient of transboundary emissions

2.3 Welfare Function

The industrial relocation and environmental management in the Beijing-Tianjin-Hebei region are divided into the following two scenarios. The initial pollution emissions of the three districts are denoted by q_1, q_2 and q_3, respectively.

2.3.1 Non-cooperative case

The polluting industries transferred out Beijing is m, the receiving quantity of Hebei is m_1, and the receiving quantity of Tianjin is m_2 ($m = m_1 + m_2$). E_i denotes the welfare function of region i.

1) Beijing's welfare function:

$$
\begin{aligned}
E_1 = {} & a_1(q_1 - m) - \frac{1}{2}(q_1 - m)^2 - \frac{1}{2}d(q_1 - m)^2 - p(q_1 - m) \\
& - \frac{1}{2}gk^2(q_1 - m)^2 + \beta_1 m + \beta_2 m - d_2^1(q_2 + m_1) - d_3^1(q_3 + m_2).
\end{aligned} \tag{2}
$$

$a_1(q_1 - m) - \frac{1}{2}(q_1 - m)^2$ denotes the production utility of Beijing after industrial relocation, $\frac{1}{2}d(q_1 - m)^2$ denotes environmental damage caused by Beijing's pollution emissions, $p(q_1 - m)$ denotes environmental tax, $\frac{1}{2}gk^2(q_1 - m)^2$ denotes the cost of emission reduction, $\beta_1 m$ denotes ecological compensation paid by Beijing for pollution control, $\beta_2 m$ denotes the central government compensates for the loss of development opportunities, $d_2^1(q_2 + m_1)$ denotes the environmental damage caused by the pollution diffusion of Hebei, $d_3^1(q_3 + m_2)$ denotes the environmental damage caused by the pollution diffusion of Tianjin.

2) Hebei's welfare function:

$$\begin{aligned}E_2 = {} & a_2(q_2+m_1) - \frac{1}{2}(q_2+m_1)^2 - \frac{1}{2}d(q_2+m_1)^2 - p(q_2+m_1) \\ & - \frac{1}{2}gk^2(q_2+m_1)^2 + \beta_1 m_1 + \beta_3 m_1 - d_1^2(q_1-m) - d_3^2(q_3+m_2).\end{aligned} \tag{3}$$

$a_2(q_2+m_1)-\frac{1}{2}(q_2+m_1)^2$ denotes the production utility of Hebei after receiving industries, $\frac{1}{2}d(q_2+m_1)^2$ denotes environmental damage caused by Hebei's pollution emissions, $p(q_2+m_1)$ denotes environmental tax, $\frac{1}{2}gk^2(q_2+m_1)^2$ denotes the cost of emission reduction, $\beta_1 m_1$ denotes ecological compensation paid by Beijing for pollution control, $\beta_3 m_1$ denotes ecological compensation paid by the central government, $d_1^2(q_1-m)$ denotes environmental damage caused by the pollution diffusion of Beijing, $d_3^2(q_3+m_2)$ denotes environmental damage caused by the pollution diffusion of Tianjin.

3) Tianjin's welfare function:

$$\begin{aligned}E_3 = {} & a_3(q_3+m_2) - \frac{1}{2}(q_3+m_2)^2 - \frac{1}{2}d(q_3+m_2)^2 - p(q_3+m_2) \\ & - \frac{1}{2}gk^2(q_3+m_2)^2 + \beta_1 m_2 + \beta_3 m_2 - d_1^3(q_1-m) - d_2^3(q_2+m_1).\end{aligned} \tag{4}$$

$a_3(q_3+m_2)-\frac{1}{2}(q_3+m_2)^2$ denotes the production utility of Tianjin after receiving industries, $\frac{1}{2}d(q_3+m_2)^2$ denotes environmental damage caused by Tianjin's pollution emissions, $p(q_3+m_2)$ denotes environmental tax, $\frac{1}{2}gk^2(q_3+m_2)^2$ denotes the cost of emission reduction, $\beta_1 m_2$ denotes ecological compensation paid by Beijing for pollution governance, $\beta_3 m_2$ denotes ecological compensation paid by the central government, $d_1^3(q_1-m)$ denotes environmental damage caused by the pollution diffusion of Beijing, $d_2^3(q_2+m_1)$ denotes environmental damage caused by the pollution diffusion of Hebei.

Take the first derivative of the welfare function E_i with respect to m, m_1, m_2, and equal to 0:

$$\frac{\partial E_1}{\partial m} = -a_1 + (d+1)q_1 - (d+1)m + p + gk^2(q_1-m) - \beta_1 + \beta_2 = 0, \tag{5}$$

$$\frac{\partial E_2}{\partial m_1} = a_2 - (d+1)q_2 - (d+1)m_1 - p - gk^2(q_2+m_1) + \beta_1 + \beta_3 = 0, \tag{6}$$

$$\frac{\partial E_3}{\partial m_2} = a_3 - (d+1)q_3 - (d+1)m_2 - p - gk^2(q_3+m_2) + \beta_1 + \beta_3 = 0, \tag{7}$$

$$m^* = \frac{-a_1 + (d+1+gk^2)q_1 + p - \beta_1 + \beta_2}{d+1+gk^2}, \tag{8}$$

$$m_1^* = \frac{a_2 - (d+1+gk^2)q_2 - p + \beta_1 + \beta_3}{d+1+gk^2}, \tag{9}$$

$$m_2^* = \frac{a_3 - (d+1+gk^2)q_3 - p + \beta_1 + \beta_3}{d+1+gk^2}, \tag{10}$$

$$\begin{aligned}m^* = m_1^* + m_2^* &= \frac{a_2 + a_3 - (d+1+gk^2)(q_2+q_3) - 2p + 2\beta_1 + 2\beta_3}{d+1+gk^2} \\ &= \frac{-a_1 + (d+1+gk^2)q_1 + p - \beta_1 + \beta_2}{d+1+gk^2},\end{aligned} \tag{11}$$

$$\frac{\partial^2 E_1}{\partial m^2} = \frac{\partial^2 E_2}{\partial m_1^2} = \frac{\partial^2 E_3}{\partial m_2^2} = -(d+1+gk^2) < 0. \tag{12}$$

2.3.2 Cooperative case

1) Overall welfare of the Beijing-Tianjin-Hebei region

The Beijing-Tianjin-Hebei region has reached a "binding" agreement to coordinate and optimize the emission reduction strategies to maximize the benefits. In the case of synergistic cooperation, regions with high economic levels introduce their advanced production technologies and management ideas to the less developed regions.

$$
\begin{aligned}
E_c = E_1^0 + E_2^0 + E_3^0 = a_1(q_1 - m_1 - m_2) - \frac{1}{2}(q_1 - m_1 - m_2)^2 - \frac{1}{2}d(q_1 - m_1 - m_2)^2 \\
- p(q_1 + q_2 + q_3) - \frac{1}{2}gk^2(q_1 - m_1 - m_2)^2 - \frac{1}{2}gk^2(q_2 + m_1)^2 - \frac{1}{2}gk^2(q_3 + m_2)^2 + a_1(q_2 + m_1) \\
- \frac{1}{2}(q_2 + m_1)^2 - \frac{1}{2}d(q_2 + m_1)^2 + a_1(q_3 + m_2) - \frac{1}{2}(q_3 + m_2)^2 - \frac{1}{2}d(q_3 + m_2)^2 + (\beta_2 + \beta_3) \\
\times (m_1 + m_2) - d_2^1(q_2 + m_1) - d_3^1(q_3 + m_2) - d_1^2(q_1 - m_1 - m_2) - d_3^2(q_3 + m_2) - \\
d_1^3(q_1 - m_1 - m_2) - d_2^3(q_2 + m_1). \qquad (13)
\end{aligned}
$$

The first derivative of the overall revenue E_c with respect to m_1, m_2, and equal to 0:

$$
\begin{aligned}
\frac{\partial E_c}{\partial m_1} &= (d + 1 + gk^2)(q_1 - q_2 - m_2) - 2(d + 1 + gk^2)m_1 \\
&\quad + \beta_2 + \beta_3 - d_2^1 + d_1^2 + d_1^3 - d_2^3 = 0, \qquad (14) \\
\frac{\partial E_c}{\partial m_2} &= (d + 1 + gk^2)(q_1 - q_3 - m_1) - 2(d + 1 + gk^2)m_2 \\
&\quad + \beta_2 + \beta_3 - d_3^1 + d_1^2 - d_3^2 + d_1^3 = 0, \qquad (15) \\
\frac{\partial^2 E_c}{\partial m_1^2} &= \frac{\partial^2 E_c}{\partial m_2^2} = -2(d + 1 + gk^2) < 0. \qquad (16)
\end{aligned}
$$

By solving the above equations simultaneously, we can obtain the following:

$$
m_1^* = \frac{(d + 1 + gk^2)(q_1 - 2q_2 + q_3) + \beta_2 + \beta_3 - 2d_2^1 + d_1^2 + d_1^3 - 2d_2^3 + d_3^1 + d_3^2}{3(d + 1 + gk^2)}, \qquad (17)
$$

$$
m_2^* = \frac{(d + 1 + gk^2)(q_1 - 2q_3 + q_2) + \beta_2 + \beta_3 - 2d_3^1 + d_1^2 + d_1^3 - 2d_3^2 + d_2^1 + d_2^3}{3(d + 1 + gk^2)}. \qquad (18)
$$

2) The economic contributions of each region

(The above data are from the National Bureau of Statistics, provincial and municipal statistics and Baidu Map).

According to the above data and the modified gravity model, the economic connection intensity model was calculated: $F_{ij} = \frac{k_{ij}\sqrt{(G_iQ_i)}\sqrt{(G_jQ_j)}}{D_{ij}^2}$, among them, $k_{ij} = \frac{G_i}{G_i + G_j}$, the degree of membership $b_{ij} = \frac{F_{ij}}{\sum_{j=1\setminus i}^{n} F_{ij}}$, and we can obtain Table 4.

Table 3 Relevant data of Beijing, Hebei and Tianjin in 2020

Region	Investment in energy conservation and environmental protection (G_i) (RMB 100 million yuan)	Total energy consumption (Q_i) (ten thousand tons)
Beijing	236.9	6762.1
Hebei	509.27	32782.76
Tianjin	60.72	8206.7
Interprovincial	Road distance (D_{ij}) (km)	
Beijing to Hebei	312	
Beijing to Tianjin	138	
Hebei to Tianjin	317	

Table 4 Economic connections in Beijing-Tianjin-Hebei

Region		Beijing	Hebei	Tianjin
Beijing	Connection		16.87	37.34
	the degree of membership		0.3112	0.6888
Hebei	Connection	36.26		25.65
	the degree of membership	0.5857		0.4143
Tianjin	Connection	9.58	3.05	
	the degree of membership	0.7585	0.2415	

Therefore, the Beijing-Tianjin-Hebei economic collaborative model is (N, T), where $N = 1, 2, 3$, representing Beijing, Hebei and Tianjin respectively in ascending order of numbers. The economic coordination matrix is as follows:

$$T = \begin{pmatrix} 0.5 & 0.156 & 0.344 \\ 0.293 & 0.5 & 0.207 \\ 0.379 & 0.121 & 0.5 \end{pmatrix}. \tag{19}$$

Then the Beijing-Tianjin-Hebei region economic coordination game is shown in Table 5. Per capita GDP of Beijing, Hebei and Tianjin in 2020 is used to measure their importance in the economic integration process of Beijing-Tianjin-Hebei, and set the weight vector $\omega = 16.8, 4.8, 9$. The Beijing-Tianjin-Hebei synergy empowerment game can be obtained as N, v_T, ω, and the proportional split-off solution of this problem is:

$$\max_{S \in 2^N \backslash \phi} \frac{v_T(S)}{\sum j \in \omega_j} = \frac{v_T(\{2\})}{\omega_2} = 0.104,\ T_1 = 2,\ x_2 = 0.5, \tag{20}$$

$$\max_{S \in 2^N \backslash \phi \backslash \{2\}} \frac{v_T(S \cup \{2\}) - v_T(\{2\})}{\sum_{j \in \omega_j}} = \frac{v_T(\{1,2,3\}) - v_T(\{2\})}{\omega_1 + \omega_3} = 0.098, \tag{21}$$

$$T_2 = \{1, 3\}, (x_1, x_3) = (1.65, 0.88). \tag{22}$$

Therefore, $\text{PSO}(N, v_T, \omega) = \{(1.65, 0.5, 0.88)\}$, corresponding to an adaptation division of $\{\{2\}, \{1, 3\}\}$. Normalizing the payment vector of PSO yields $0.545, 0.165$ and 0.29, which indicates that the contributions of Beijing, Hebei and Tianjin to the economic synergy of the Beijing-Tianjin-Hebei region in 2020 is $54.5\%, 16.5\%$ and 29%, respectively. The benefits of the three districts are distributed according to their contributions: $E_1^* = 0.545E_C^*$, $E_2^* = 0.165E_C^*$, $E_3^* = 0.29E_C^*$.

Table 5 The Beijing-Tianjin-Hebei Economic Collaborative Game

$S \in 2^N$	ϕ	$\{1\}$	$\{2\}$	$\{3\}$	$\{1,2\}$	$\{1,3\}$	$\{2,3\}$	$\{1,2,3\}$
$v_T(S)$	0	0.5	0.5	0.5	1.448	1.724	1.328	3

3 Numerical Analysis

According to the model solution and analysis above, it can be seen that the optimal relocation quantities are different in the non-cooperative and cooperative scenarios. To further verify the scientificity of the solution results as well as to compare and analyze the impact on the equilibrium strategy under different relocation quantities and subsidy levels, the numerical values of the above benchmark parameters are substituted into each formula, as shown in Table 6. The parameter a_1, a_2, a_3, p, and d are set according to Jiang and You[29], k is derived from the calculation of Equation (11) in the text, and the rest of the parameters are reasonably set considering the actual condition in the Beijing-Tianjin-Hebei Region.

Table 6 Numerical parameter setting

Parameter	numerical value	Parameter	numerical value
q_1	20	p	2
q_2	6	d	0.5
q_3	10	g	0.3
a_1	20	β_1	6
a_2	10	β_2	4
a_3	15	β_3	3
k	0.68	d_i^1	0.2
d_i^2	0.1	d_i^3	0.1

According to this parameter setting, the welfare of the three districts in the two scenarios is calculated as shown in Table 7.

It can be seen that the quantity of transferring or receiving in the cooperative case is more than that in the non-cooperative case. Beijing can only shift 7.8 units of polluting industries in the non-cooperative scenario, while it is 10.9 units in the cooperative case. The receiving quantities of Hebei and Tianjin also increase in the cooperative case, so the revenues are greater than those in the non-cooperative case. The overall revenue of Beijing, Tianjin and Hebei in the non-cooperative case is 164, while it is 350 in the cooperative case, indicating that the synergistic cooperation is beneficial.

MATLAB is used to simulate the optimal relocation quantity m^* and the changing trend of welfare level within the limited relocation quantity in the two scenarios.

Table 7 Relocation quantity and welfare in the two scenarios

Non-cooperative case	Cooperative case
transferring quantity of Beijing $m_* = 7.8$	transferring quantity of Beijing $m_* = 10.9$
receiving quantity of Hebei $m_1^* = 4.4$	receiving quantity of Hebei $m_1^* = 7.4$
receiving quantity of Tianjin $m_2^* = 3.4$	receiving quantity of Tianjin $m_2^* = 3.5$
Beijing revenue $E_1 = 77.3$	Beijing revenue $E_1 = 0.545E_C^* = 190.75$
Hebei revenue $E_2 = 31.6$	Hebei revenue $E_2 = 0.165E_C^* = 57.75$
Tianjin revenue $E_3 = 55.1$	Tianjin revenue $E_3 = 0.29E_C^* = 101.5$
Overall revenue $E_N^* = 164$	Overall revenue $E_C^* = 350$

As can be seen in Figure 1, in the non-cooperative case, with the growth of relocation quantity of polluting industries, the welfare of the three districts all show a trend of increase before decrease. The revenue of Beijing shows an upward trend between the interval $[0, 7.8]$. When the transferring quantity is greater than 7.8, the benefit begins to show a downward trend, that is, when the transferring quantity m^* is 7.8, the maximum welfare reaches 77.3. The revenue of Hebei shows an upward trend between 0 and 4.4. When the receiving quantity m_1^* is 4.4, the maximum revenue reaches 31.6. The revenue begins to decline when the receiving quantity m_1^* is more than 4.4. Similarly, the revenue of Tianjin shows an upward trend in the interval $[0, 3.4]$. When the receving quantity exceeds 3.4, the revenue begins to decline, that is, the optimal receiving quantity of Tianjin m_2^* is 3.4, and the maximum revenue at this time is 55.1. From the perspective of welfare, it shows that receiving polluting industries has a limited effect on the economic growth, when it exceeds a certain quantity, the local welfare declines. Regions cannot simply transfer out polluting industries in pursuit of a cleaner environment.

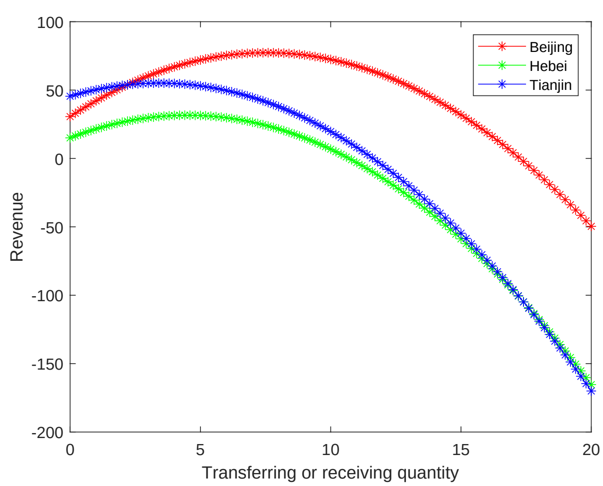

Figure 1 Relationship between welfare and transferring (receiving) quantity in each region

As can be seen in Figure 2, as the subsidy paid by Beijing to the receiving regions increases, the revenue of the receiving regions both increase with it. It shows that the larger the ecological compensation paid by Beijing to the receiving region, the more the receiving region benefits and the higher the willingness to undertake polluting industries; Slightly difference is that the revenue of Tianjin grows relatively slowly when the subsidy is smaller, and the revenue increases significantly as the subsidy increases. Therefore, the willingness to undertake polluting industries in Tianjin can be enhanced by increasing the subsidy.

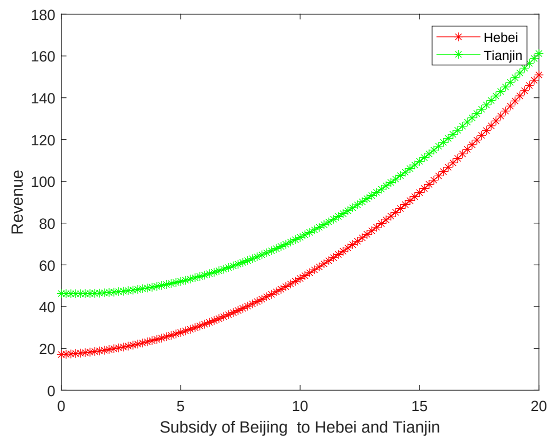

Figure 2 Relationship between welfare and the ecological subsidy paid by Beijing

In Figure 3, it can be seen that in the non-cooperative scenario, the welfare of three regions increases with the increase of the central subsidy, indicating that the central government subsidy have a positive effect in promoting Beijing to transfer industries out and other regions to receive industries. It can also be observed that when the central government subsidy implemented, the increase in the benefit function of Beijing is more significant than that of the receiving region. When the central government subsidy is smaller, the benefit increase of Tianjin is relatively slower, and as the subsidy increases, the growth trend of benefit is obvious. Therefore, the central government can increase subsidy to motivate the three regions to transfer out or receive polluting industries.

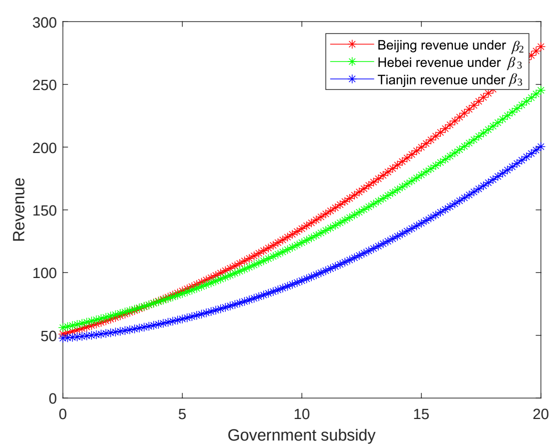

Figure 3 Relationship between welfare and the central government subsidy in non-cooperative case

In the cooperative scenario, with the growth of undertaking quantity of Hebei and Tianjin, the overall welfare shows a trend of increasing at first and then decreasing. For the undertaking quantity of Hebei m_1^*, in the interval $[0, 7.4]$, the overall welfare also rises with the increase of undertaking quantity. When the undertaking quantity m_1^* reaches 7.4, at this time, the overall revenue reaches the maximum value of 350. When the undertaking quantity m_1^* exceeds 7.4 and increases again, the overall welfare shows a downward trend. It indicates a critical point 7.4 when Hebei undertakes polluting industries. When exceeding a certain threshold, Hebei undertakes polluting industries will have a negative impact on the overall welfare, and the overall welfare will show a downward trend. In the interval $[0, 3.5]$, with the increase of undertaking quantity of Tianjin m_2^*, the overall welfare also rises for the undertaking quantity. When the undertaking quantity m_2^* reaches 3.5, the overall revenue reaches the maximum of 350. When the undertaking quantity m_2^* exceeds 3.5 and increases again, overall welfare declines. It shows that from the perspective of overall interests, Hebei and Tianjin cannot receive polluting industries without limits.

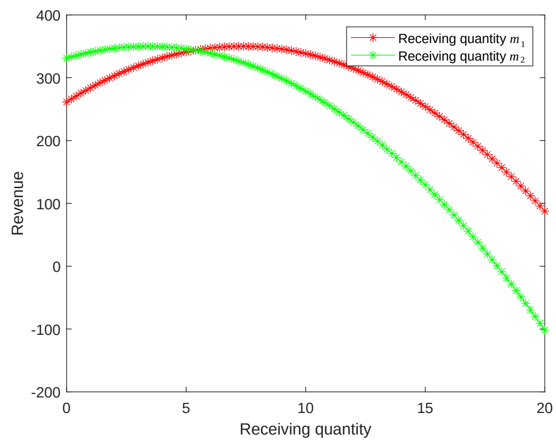

Figure 4 Overall welfare in the cooperative case

4 Conclusions and Suggestions

We construct the welfare functions considering the ecological subsidy mechanism of the central government and local governments in the context of industrial relocation in Beijing, Tianjin and Hebei. Then we solve the optimal relocation quantity and the optimal revenue in the Beijing, Tianjin and Hebei region in different cases. It is found that: 1) the optimal strategy in the region is closely related to utility coefficient, environmental loss coefficient and incentive intensity coefficient. 2) In the non-cooperative case, the ecological compensation paid by the central government to the transfer-out city has an important influence on the equilibrium strategy of the region. 3) The welfare and the quantity of industrial relocation in the cooperative case are significantly greater than those in the non-cooperative case.

Based on the above, some suggestions are made:

Firstly, the central government should play leading role in the process of environmental governance in Beijing-Tianjin-Hebei. It should coordinate the interests of all parties, break the administrative barriers between local governments, and ensure reasonable industrial relocation and stable cooperation. Secondly, given the disparity in economic development levels among Beijing, Tianjin, and Hebei, relevant ecological governance incentives and preferential policies should be introduced to promote the implementation of industrial transfer in the Beijing-Tianjin-Hebei region. Finally, Beijing, Hebei and Tianjin should reasonably carry out industrial relocation according to the actual situation, actively participate in collaborative governance, and achieve regional economic development while controlling pollution.

References

[1] Guo Y, Zeng Z, Tian J, et al. Uncovering the strategies of green development in a Chinese province driven by reallocating the emission caps of multiple pollutants among industries. Science of the Total Environment, 2017, 607: 1487–1496.

[2] Li T, Liu Y, Wang C, et al. Decentralization of the non-capital functions of Beijing: Industrial transfer and its environmental effects. Journal of Cleaner Production, 2019, 224: 545–556.

[3] Yang X L, Zhang S Y. Simulation study of industrial transfer policy in Beijing, Tianjin and Hebei province based on multi-regional CGE model. Forum on Science and Technology in China, 2019(2): 83–89.

[4] Chen W, Shen Y, Wang Y, et al. The effect of industrial relocation on industrial land use efficiency in China: A spatial econometrics approach. Journal of Cleaner Production, 2018, 205: 525–535.

[5] Wang Z, Chen S, Cui C, et al. Industry relocation or emission relocation? Visualizing and decomposing the dislocation between China's economy and carbon emissions. Journal of Cleaner Production, 2019, 208: 1109–1119.

[6] Yuan S Y, Sun X P, Chen W G, et al. Study on the measurement of industrial structure "sophistication, rationalization and ecologicalization" based on the dynamic analysis of grey relations — A case study of Beijing-Tianjin-Hebei. Journal of Systems Science and Information, 2020, 8(2): 130–147.

[7] Lin B, Wang C. Does industrial relocation affect regional carbon intensity? Evidence from China's secondary industry. Energy Policy, 2023, 173: 113339.

[8] Peng Y, Zhu H, Cui J. Changes in environmental performance with firm relocation and its influencing mechanism: An evidence of chemical industry in Jiangsu, China. Journal of Environmental Management, 2023, 336: 117712.

[9] Jiang Z, Lyu P. Stimulate or inhibit? Multiple environmental regulations and pollution-intensive industries' transfer in China. Journal of Cleaner Production, 2021, 328: 129528.

[10] Liu X, Wang W, Wu W, et al. Using cooperative game model of air pollution governance to study the cost sharing in Yangtze River Delta Region. Journal of Environmental Management, 2022, 301: 113896.

[11] Yang M, Xie Z Y, Xu F. A study of inter-provincial carbon transfer under regional sequential CO_2 peak in China. Systems Engineering — Theory & Practice: 1–23[2023–05–17]. http://kns.cnki.net/kcms/detail/11.2267.n.20230425.1128.003.html.

[12] Wang H, Zhao L, Xie Y, et al. "APEC blue" — The effects and implications of joint pollution prevention and control program. Science of the Total Environment, 2016, 553: 429–438.

[13] Xu L, Di Z, Chen J. Evolutionary game of inland shipping pollution control under government co-supervision. Marine Pollution Bulletin, 2021, 171: 112730.

[14] Wang Y, Zhao Y. Is collaborative governance effective for air pollution prevention? A case study on the Yangtze River Delta Region of China. Journal of Environmental Management, 2021, 292: 112709.

[15] Wang L G, Zhang Q, Wang L, et al. Air pollution, environmental regulations and economic growth — Estimation of simultaneous equations based on panel data of prefecture-level cities. Journal of Systems Science and Information, 2021, 9(6): 721–738.

[16] Zhang G, He N. The proportional split-off solution for cooperative games and application in regional economic integration. Journal of Systems Science and Mathematical Sciences, 2022, 42(4): 791–801.

[17] Qu L, Chai F, Liu S, et al. Comprehensive evaluation method of urban air quality statistics based on environmental monitoring data and its application. Journal of Environmental Sciences, 2023, 123: 500–509.

[18] Luo X, Tang X, Wang H, et al. Investigating the changes in air pollutant emissions over the Beijing-Tianjin-Hebei Region in February from 2014 to 2019 through an inverse emission method. Advances in Atmospheric Sciences, 2023, 40(4): 601–618.

[19] Lin Y, Yu Z W, Wang Y M. Closed-loop supply chain emission reduction and coordination under carbon tax policy and risk aversion. Journal of Systems Science and Mathematical Sciences: 1–16[2023–05–17]. http://kns.cnki.net/kcms/detail/11.2019.o1.20230329.0935.004.html.

[20] Yang W, Gong Q, Zhang X. Surplus or deficit? Quantifying the total ecological compensation of Beijing-Tianjin-Hebei Region. Journal of Geographical Sciences, 2020, 30(4): 621–641.

[21] Zheng Q, Wan L, Wang S, et al. Does ecological compensation have a spillover effect on industrial structure upgrading? Evidence from China based on a multi-stage dynamic DID approach. Journal of Environmental Management, 2021, 294: 112934.

[22] Wang W, Wu F, Yu H. Optimal design of the ecological compensation mechanism in transboundary river basins under the Belt and Road Initiative. Sustainable Production and Consumption, 2022, 32: 173–183.

[23] Ling X Y, Meng W D, Huang B. Research on cooperative governance strategy of transboundary pollution based on multiple pollutants damage and ecological compensation. Management Review, 2022, 34(12): 288–301.

[24] Wang D P, Yin Y B, Dong H X. Research on carbon emission reduction strategies considering government subsidies and manufacturers' reciprocal preferences. Journal of Systems Science and Mathematical Sciences: 1–21[2023–05–17]. http://kns.cnki.net/kcms/detail/11.2019.O1.20230221.1350.018.html.

[25] Ministry of Industry and Information Technology of the People's Republic of China. Beijing-Tianjin-Hebei Industrial Relocation Guidelines, 2016–06–29. https://www.miit.gov.cn/.

[26] Jørgensen S, Zaccour G. Incentive equilibrium strategies and welfare allocation in a dynamic game of pollution control. Automatica, 2001, 37(1): 29–36.

[27] Breton M, Zaccour G, Zahaf M. A differential game of joint implementation of environmental projects. Automatica, 2005, 41(10): 1737–1749.

[28] Yeung D W K. Dynamically consistent cooperative solution in a differential game of transboundary industrial pollution. Journal of Optimization Theory and Applications, 2007, 134(1): 143–160.

[29] Jiang K, You D M. Study on differential game of transboundary pollution control under regional ecological compensation. China Population, Resources and Environment, 2019, 29(1): 135–143.

[30] Poyago-Theotoky J A. The organization of R&D and environmental policy. Journal of Economic Behavior and Organization, 2007, 62(1): 63–75.