# Network-Based Pollutant Emission Allowance Allocation Optimization and Impact Assessment for Industrial Parks

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## Abstract

Industrial parks are key meso-scale units linking regional environmental capacity with firm-level emission control. Existing allowance-allocation approaches based on emission standards, environmental capacity, or pollution performance often treat firms as independent emitters and overlook inter-firm linkages. This study proposes a network-informed emission-allowance allocation framework that integrates industrial network construction, agent-based modeling (ABM), and allocation optimization. Using patents, product information, market scope, process-flow matching, and invoice transactions, we construct three inter-firm networks: technological cooperation, product competition, and supplier–customer relationships. Firm decisions on production, technology upgrading, and spatial adjustment are simulated using an ABM based on the Theory of Planned Behavior. Allowances are then optimized by combining historical emissions, pollution performance, and network importance, with an initial 80/20 weighting of historical responsibility and performance incentives.When applied to the Beijing–Tianjin–Hebei region, the results show that Hebei firms cooperate more strongly with leading Beijing firms than with firms within Hebei. Hebei firms also face intense product competition, while supplier–customer ties are mainly concentrated within the province. Supplier distance, registered capital, and abnormal-operation records are identified as key determinants of core supplier relationships. A case study of Langfang City in Hebei Province further shows that zones with high industrial agglomeration and frequent supply-chain interactions can receive moderately higher allowances, whereas allowances for weakly connected zones can be reduced or held constant. The framework improves the realism, fairness, and enforceability of differentiated emission allocation.

**Keywords:** industrial park; industrial network; agent-based modeling; pollutant allowance allocation; ecological-environmental zoning-based regulation

## 1 Introduction

Environmental governance increasingly requires economic activities to operate within environmental capacity and emission limits. Existing studies have provided important insights at both ends of the scale spectrum: macro-scale studies emphasize planetary boundaries, regional carrying capacity, and total emission control, while micro-scale studies focus on technology-specific standards, facility-level control, and end-of-pipe treatment. However, many environmental management decisions are implemented at the meso-scale, including regions, watersheds, industrial parks, and ecological-environmental regulatory units. At this scale, broad environmental constraints must be translated into operational rules for firms and industrial clusters.

Industrial parks are typical meso-scale governance units. They concentrate industrial firms, production activities, and pollutant emissions, while also supporting regional economic growth and industrial coordination. Their internal structures are highly heterogeneous in terms of firm size, sectoral composition, technology level, energy use, and environmental pressure. In China, ecological-environmental zoning-based regulation (EZR) provides a spatially differentiated framework by dividing land into integrated ecological and environmental units and imposing different requirements on spatial layout, emission control, pollution-control technology, and risk prevention. Nevertheless, EZR still leaves a key allocation question unresolved: under fixed environmental capacity and total emission control targets, who should bear more reduction responsibility, and how should emission allowances be distributed among regions, parks, and firms?

Existing allowance-allocation methods mainly rely on emission standards, environmental capacity, or pollution performance. These approaches support total-emission decomposition but generally assume that firms or regions are independent emission units. This assumption is problematic for industrial parks, where firms are embedded in supplier–customer relationships, product competition, and technological cooperation. These inter-firm linkages can influence production scale, technology upgrading, pollution-control investment, and spatial adjustment. They may also transmit, amplify, or shift the effects of environmental regulation across firms and regions. Ignoring such network effects may therefore lead to allocation rules that are less realistic, less efficient, and harder to implement.

To address this gap, this paper develops a network-informed emission-allowance allocation framework for industrial parks. The framework first constructs technological-cooperation, product-competition, and supplier–customer networks using multi-source firm-level data. It then simulates firm behavioral responses under the joint influence of EZR and industrial networks using an ABM. Finally, it integrates historical emissions, pollution performance, and network importance into allocation optimization. The objective is to support a more realistic and implementable allocation scheme that balances environmental fairness, economic efficiency, and industrial-chain stability.

# 2 Methods

## 2.1 Overall framework

The framework (Fig. 1) follows three steps: industrial-network construction, firm-behavior simulation, and allowance-allocation optimization. Industrial firms are first defined as network nodes. Three inter-firm relationship layers are then constructed and quantified. The resulting networks are embedded into an ABM to simulate annual firm decisions on production, technology upgrading, and spatial adjustment under EZR constraints. Firm-level decisions are translated into pollutant emissions, and the final allocation scheme is optimized under a fixed regional total-emission cap.

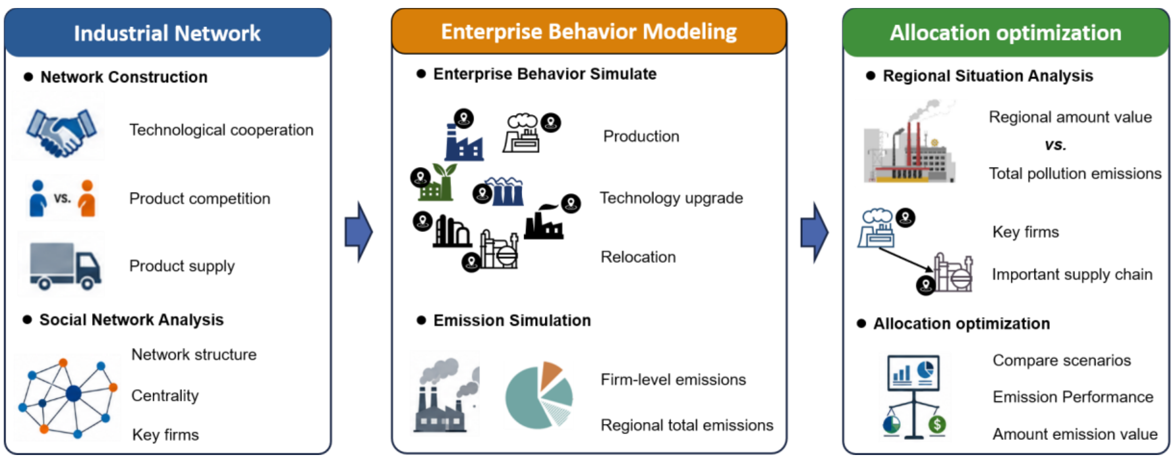


Fig.1 Framework of this study

## 2.2 Industrial network construction

Three network layers are constructed. The technological-cooperation network is identified from joint invention-patent records. If two firms co-apply for the same patent, an undirected cooperation edge is created. Edge strength is measured using the number of joint applications, cooperation continuity, and the most recent cooperation year.The product-competition network is constructed from product type, industry category, and market service scope. Two firms are linked when they produce identical or similar products and their service areas overlap. Edge strength is calculated from product similarity and market-overlap intensity, representing potential competitive pressure.

The supplier–customer network is constructed in two stages. First, potential supply links are generated through raw-material–product matching and process-flow matching. A firm is treated as a potential upstream supplier when its product can serve as another firm's raw material, intermediate input, or process input. Second, invoice transaction data are used to validate, rank, and filter these potential links. Supplier-selection factors, such as transaction frequency, transaction value, cooperation persistence, and matching quality, are used to identify real supplier–customer relationships and assign edge weights. After the three network layers are obtained, social network analysis is applied to calculate node degree, in-degree, out-degree, betweenness centrality, and network density. These indicators are used to identify key firms, important industrial links, and regulatory units with high industrial-system importance.

## 2.3 Firm-behavior and emission simulation

Each firm is modeled as an autonomous agent with attributes including industry type, production scale, technology level, emission intensity, spatial location, host integrated ecological and environmental unit (IEEU), and EZR constraints. The model runs at an annual time step. At each step, firms update three decisions: production adjustment, technology upgrading, and spatial adjustment.

Firm decision rules are based on the Theory of Planned Behavior and are operationalized through three inputs: behavior preference, interaction impact, and cost–benefit judgment. EZR constraints affect compliance pressure and perceived risk. Production cost, operating profit, and pollution-control cost determine the cost–benefit term. Industrial-network effects enter the interaction term: supplier–customer ties affect production stability and order changes; competition ties affect market pressure and technology following; and cooperation ties affect the probability of cleaner-technology diffusion.

For each decision type, the model estimates a behavioral tendency score and converts it into an action probability. The selected actions update firm status, including production scale, technology level, location, and emission intensity. Pollutant emissions are then recalculated from updated production and emission-intensity parameters. The simulation outputs firm distribution, industrial agglomeration, and pollutant emissions by regulatory unit and pollutant type.

### 2.4 Allowance-allocation optimization

Allowance allocation is optimized under the regional total-emission cap. Three normalized indicators are used: historical emissions, pollution performance, and network importance. Historical emissions represent existing emission responsibility. Pollution performance is measured as economic output per unit of pollutant emission. Network importance is measured by the firm's or unit's position in the supplier–customer network and its role in industrial-chain connectivity.

The procedure has three steps. First, regulatory units are classified into allowance-surplus and allowance-constrained zones according to environmental capacity, current emissions, and total-control targets. Second, strongly connected upstream and downstream units are grouped as coordinated allocation units to avoid separating highly dependent supply-chain partners. Third, the initial allowance is calculated by combining normalized historical emissions and pollution performance with an 80/20 weighting. The allocation is then adjusted according to network importance and re-normalized so that the sum of all allocated allowances remains equal to the fixed total cap.This design does not relax total-emission control. It redistributes a fixed emission space across regulatory units while considering historical responsibility, efficiency incentives, and supply-chain stability.

## 3 Case Area and Results

### 3.1 Case area

The Beijing–Tianjin–Hebei (BTH) region is used as the study area. BTH hosts a large number of industrial parks and manufacturing clusters, including equipment manufacturing, bio-pharmaceuticals, food processing, steel, furniture, and paper-making, with pronounced cross-regional trade and inter-regional industrial flows. Hebei is a traditional industrial province and a major recipient of industrial transfer and supply-chain coordination from Beijing and Tianjin. BTH also has a high share of critical-regulatory units and substantial emission pressure, making it well suited for analyzing the relationship among industrial networks, firm behavior, and allowance allocation.

### 3.2 Industrial network characteristics

The three network layers display distinct spatial patterns. In technological cooperation, Hebei firms tend to cooperate with leading firms in Beijing, while intra-Hebei cooperation is comparatively rare, indicating Beijing's innovation-leading role. In product competition, Hebei firms face intense market pressure: many firms produce similar products and serve overlapping markets. In supplier–customer relationships, Hebei firms show pronounced intra-provincial embeddedness, with most principal suppliers and customers located within Hebei.

The results show that suppliers located closer to the focal firm, with larger registered capital and fewer records of abnormal business operation, are more likely to become core suppliers. Firm size significantly affects the scale of the supply network: micro and small firms have substantially fewer supply-network ties than medium-sized firms and rely more heavily on local suppliers. Upstream and downstream linkages also vary across industrial chains. In the chemical industry, both the number of local suppliers and the number of local customers are higher than in other industrial chains. Overall, technological cooperation is more cross-regional, competition is dense, and supply-chain linkages are locally concentrated. The scale of the industrial network is shown in Fig. 2.

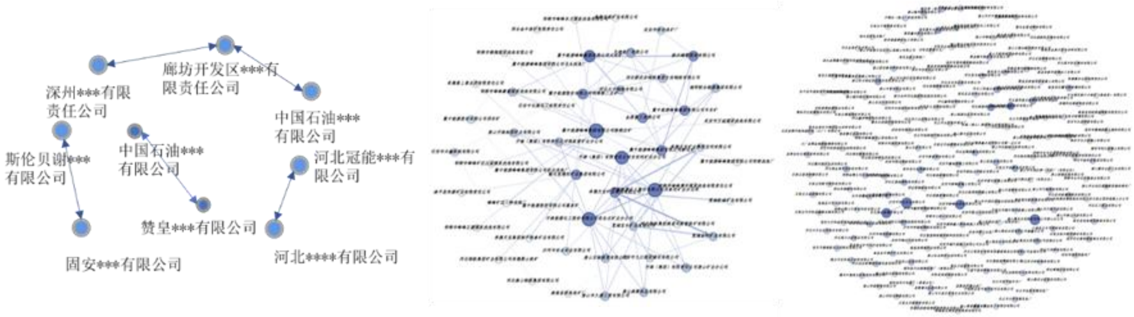


Fig.2 Scale of industry network

### 3.3 Firm-behavior simulation results

Simulation under network and zoning constraints shows that EZR reshapes firms' spatial layout and emissions. Under regulation, firms become more concentrated in critical-regulatory units (IEEU-C), while overall emissions decline, indicating source-prevention and spatial-control effects. Comparing 2020 and 2025, simulated firm numbers and emissions contract most sharply in protect-in-prior units (IEEU-P), falling by roughly 96%–100%; ordinary-restriction units (IEEU-O) decline moderately, generally by about 35%–49%; and critical-regulatory units remain comparatively stable or slightly increase, by about 1%–16%. Firms also tend to cluster around regional boundary areas, which may reflect transitional regulatory intensity, enforcement differences, and siting strategies.

### 3.4 Allocation-optimization results

Allocation optimization is illustrated with Langfang City in Hebei Province, whose industrial chains include steel, wood and furniture, paper-making and printing, equipment manufacturing, non-ferrous metals, and food. The most significant emitters are concentrated in traditional pollution-intensive chains, especially steel smelting, furniture, and paper-making. Areas with high industrial agglomeration, frequent supply-chain interactions, and important industrial-chain functions can be assigned moderately higher allowances because abrupt cuts may destabilize upstream and downstream chains. Allowances for areas with weak linkages, less important industrial-chain functions, or low pollution performance can be reduced or held constant.

The regional total remains fixed; optimization only reallocates emission space more purposefully. The adjustment space also differs by pollutant, as $SO_2$, VOCs, and PM2.5 vary in sources, sectoral contributions, and treatment potential. The results are shown in Fig. 3.

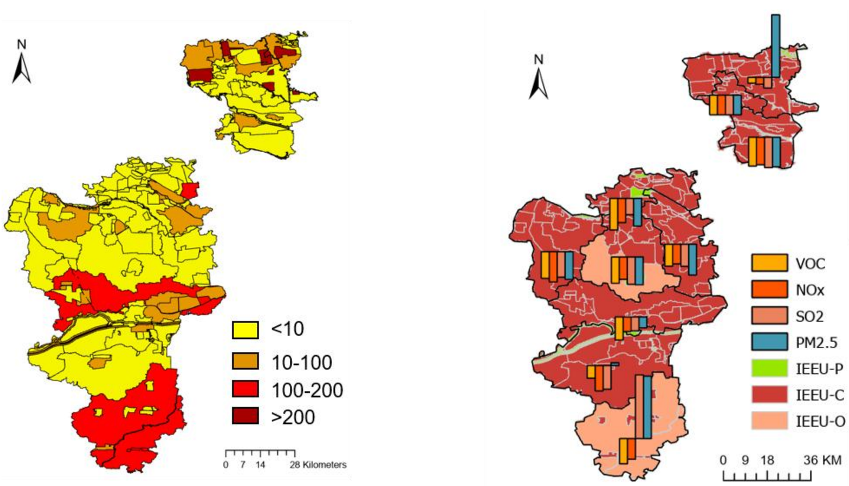


Fig.3 $SO_2$ emission allowance of different zones and different allocation optimization strategies of air pollutant

## 4 Discussion and Policy Implications

Industrial networks significantly influence firm behavior and emission outcomes. A firm's emissions are shaped not only by its own scale, technology level, and treatment capacity, but also by its supplier–customer, competition, and cooperation relationships. Park-level management and firm-level regulation should therefore adopt a network perspective rather than treating firms as isolated emission sources. EZR operates through spatially differentiated constraints, but its effects are mediated by firms' supply-chain positions, supply stability, and competitive pressure. Accordingly, allowance allocation should shift from an isolated-unit logic to a network-informed logic, improving fairness, efficiency, and enforceability while avoiding excessive shocks to key industrial chains.

Looking ahead, China needs stronger full-chain coordination among environmental impact assessment, ecological-environmental zoning regulation, and pollutant discharge permitting. AI can support this process by extracting policy constraints, matching emission data, and coupling these inputs with ABM to explore firm behavior and regional emission changes under alternative scenarios. AI does not replace environmental decision-making, but it can support more integrated, dynamic, and adaptive environmental management.

## 5 Conclusion

This paper proposed a network-informed emission-allowance allocation framework that integrates industrial networks and ABM, and applied it to the BTH region and Langfang City. The results show that inter-firm technological cooperation, product competition, and supplier–customer relationships shape firm behavior and emissions; EZR influences firm layout and emissions through spatially differentiated constraints, whose effects depend on network relationships; and allowance allocation should jointly consider historical emissions, pollution performance, and network importance under a fixed total cap. The framework provides methodological support for regional total-emission management, differentiated industrial-park regulation, and coordination across environmental-management institutions.

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