



International Journal of Global Warming

ISSN online: 1758-2091 - ISSN print: 1758-2083

<https://www.inderscience.com/ijgw>

Efficiency of environmental regulation oversight in the cement sector: compliance and development within the framework of inspection on government

Xiang Yi, Shixiao Liu

DOI: [10.1504/IJGW.2025.10068660](https://doi.org/10.1504/IJGW.2025.10068660)

Article History:

Received:	03 March 2024
Last revised:	25 October 2024
Accepted:	25 October 2024
Published online:	10 January 2025

Efficiency of environmental regulation oversight in the cement sector: compliance and development within the framework of inspection on government

Xiang Yi*

Business School,
Dongguan City University,
Dongguan, 523419, China
Email: xiang.yi@outlook.com
*Corresponding author

Shixiao Liu

Public Health School,
Guangdong Pharmaceutical University,
Guangzhou, 510006, China
Email: shixiao.liu@outlook.com

Abstract: This study investigates the role of environmental regulations in balancing ecological conservation and cement industry development within the ‘inspection on government’ framework. Results show that implementing stringent environmental regulations and low industrial agglomeration levels while suppressing FDI can achieve a ‘win-win’ scenario for carbon reduction and maximising cement shipments. However, if FDI exceeds historical levels, consistently enforcing strict regulations and maintaining high industrial agglomeration are necessary. Additionally, when the market control variables satisfy the conditions of the ‘optimisation trap’, the maximum value of cement shipment remains lower than the results obtained from varying any single market variable. Furthermore, the ‘optimisation trap’ undermines the efficacy of our policy control variables adjustments, as any values assigned to the policy control variables become irrelevant to the optimisation procedure.

Keywords: environmental regulation; inspection on government; SMLR; GAs

Reference to this paper should be made as follows: Yi, X. and Liu, S. (2025) ‘Efficiency of environmental regulation oversight in the cement sector: compliance and development within the framework of inspection on government’, *Int. J. Global Warming*, Vol. 35, No. 1, pp.51–83.

Biographical notes: Xiang Yi is an Associate Professor at Dongguan City University, with a PhD in Applied Mathematics from the University of Nottingham. His research interests primarily centre around environmental regulatory decision-making, the interplay between gradient economics and low-carbon development, identifying optimal investment timing within the green building industry, leveraging machine learning and statistical models for data analysis.

Shixiao Liu is a Lecturer at Guangdong Pharmaceutical University, with a PhD in Environmental Science and Engineering from the University of Nottingham. Her research focuses on electronic waste management, water footprint analysis, wastewater treatment, and the study of disinfection by-product formation and control in drinking water.

1 Introduction

In the epoch of industrial civilisation, the creation of substantial wealth has been paralleled by an acceleration in the consumption of natural resources and a concurrent rise in global energy-related emissions (Leffel et al., 2022). The International Energy Agency reports a 0.9% increase from 2021 to 2022, underscoring the urgency of addressing environmental impacts (Cozzi et al., 2023). This trend is particularly pronounced in the cement industry, which, due to its high pollution and energy intensity, faces significant challenges in aligning economic expansion with ecological sustainability amidst a global surge in infrastructure projects (Garatti et al., 2021; Chaudhary et al., 2021; Mishra et al., 2022; Jena et al., 2020). The industry's carbon emissions, at an average of 6.9 kg/USD per unit of income, significantly exceed those of sectors like steel and oil and gas (Mallagray et al., 2021), thus presenting a formidable challenge for policymakers seeking to reconcile ecological conservation with economic advancement.

Environmental regulations constitute a critical governmental intervention aimed at rectifying market failures in environmental externalities and fostering a harmonious co-development of economic and ecological systems (Fiorino, 2006). The 'pollution haven hypothesis' (PHH) posits that stringent regulations may precipitate industrial relocation to regions with more lenient standards (Singhanian and Saini, 2021; Duan et al., 2021). In contrast, the 'Porter hypothesis' (P.H.) suggests that appropriately stringent environmental regulations can act as a catalyst for innovation, potentially leading to cost reductions and technological advancements (Porter et al., 1995). The 'environmental Kuznets curve hypothesis' introduces a nuanced perspective, proposing an inverted U-shaped curve between economic development and environmental degradation, indicating that environmental quality may initially decline but subsequently improve with sustained economic growth (Dinda, 2004; Wang et al., 2019).

Against this theoretical backdrop, the study zeroes in on the cement industry to explore the practical application of environmental regulations in achieving a delicate balance between ecological stewardship and industrial progress. China, a global leader in cement production and a consumer of over 7% of the nation's total fuel (Bildirici, 2019), exemplifies the complexities inherent in this endeavour. In response to the significant challenges of air pollution and noise pollution in the cement sector, the Chinese government has set forth a roadmap for ultra-low emission transformations in cement clinker production facilities. With a strategic goal for half of the facilities in key air pollution control regions to complete this transformation by the end of 2025, and an ambitious plan to extend this to 80% of the nation's overall cement clinker production capacity by 2028, these initiatives are pivotal steps towards reducing the industry's emissions and environmental impact. These efforts not only consolidate previous achievements in emission reductions but also position China to lead in fostering international cooperation and averting ecological backsliding. This study seeks to

elucidate the interplay between industrial-economic development and ecological considerations within the ‘inspection on government’ framework, a governance paradigm with broad international relevance. By examining the efficacy of environmental regulations in balancing ecological conservation with the growth of the cement industry, the research delves into the impact of policy control variables on carbon dioxide emissions per unit of cement produced and overall cement shipment volumes. Employing a generalised linear model (GLM), the study uncovers significant correlations and formulates strategies for adjusting policy control variables to harmonise ecological preservation with industrial expansion. This analysis is pivotal for crafting effective strategies that can navigate the global developmental dichotomy, where the imperatives of ecological protection and economic prosperity must intersect and thrive in tandem.

The paper is meticulously structured to offer a comprehensive analysis of the interplay between environmental governance and the cement industry. It begins with Section 2, which provides an in-depth examination of China’s environmental governance framework, detailing the roles and responsibilities distributed across various levels of environmental regulatory bodies and analysing their interrelationships. Utilising a rich dataset from 1989 to 2020, this section captures annual metrics such as cement production, shipment volumes, average mill prices, and air pollutant emission standards within the cement industry. Provincial data is integrated to offer a nuanced depiction of market dynamics, the degree of industrial clustering, and the fluctuations in environmental regulatory stringency. Section 3 employs GLMs constructed through a stepwise regression approach, to elucidate significant correlations between average carbon dioxide emissions per ton of cement and key factors such as industrial agglomeration, environmental regulation intensity, and market characteristics. It further explores the relationship between cement shipment volumes and these variables. Section 3.2 conducts numerical simulations to assess how different levels of environmental regulation intensity and market features across various industrial agglomeration levels affect average carbon dioxide emissions and cement shipment volumes, proposing tailored strategies to harmonise ecological conservation with industrial advancement under specific market conditions. Section 4 delves into optimal strategies under constrained conditions, employing genetic algorithms (GAs) and model analysis to construct an optimal function aimed at maximising cement shipment volumes while aligning with decarbonisation goals and navigating the challenges of ‘optimisation traps,’ as informed by the regression model outcomes. The paper culminates in Section 5 with a concise conclusion, synthesising the findings and highlighting the optimal policy directives for striking a balance between ecological preservation and industrial expansion within the cement industry.

2 Materials and method

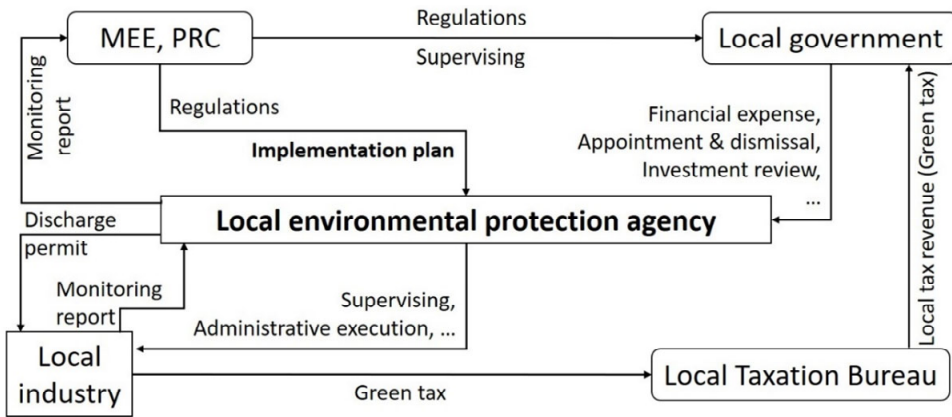
2.1 Preliminaries

The model of ‘inspection on government’ is a regulatory approach that heavily relies on administrative measures employed by the government. Such a model is characterised by its reliance on the government performance evaluation system of the state to achieve regulatory objectives, especially in developing countries like China. Generally, ‘command-and-control’ environmental regulations play a more crucial role in the

governance system of such a regulatory approach than other environmental regulations (Huang and Yang, 2016). Using China as a case study, the environmental regulation and governance process involves many laws and policies, but the state plan (such as the state five-year plan) is the primary driver. In addition to the state five-year plan and other national plans, there are periodic or irregular mid-crisis scanning procedures and policy responses (Young et al., 2015). In this regulatory approach of ‘inspection on government’, as depicted in Figure 1, the Ministry of Ecology and Environment (MEE) – the central environmental department – is empowered to oversee environmental issues that occur nationwide and also to develop relevant regulations, policies, standards, and other related documents. These have a binding force on enterprises, institutions, and individuals throughout the country and are not subject to influence from local governments. The local environmental protection agency (at the city level) plays a significant role in ensuring the quality of the local environment and ecological safety. Its primary responsibilities include promoting local enterprise environmental protection and penalising environmental violations by implementing relevant regulations and policies formulated by the central environmental department. The department also conducts environmental monitoring and evaluation by gathering, analysing, and publishing information related to environmental quality, pollutant sources, and emissions and reporting it to the central environmental department as a report. Furthermore, the department is accountable for promptly releasing environmental alerts and warnings.

Note that although the local environmental protection agency receives guidance and supervision from the higher-level environmental department, personnel and financial management come under the local government’s purview. The local government is responsible for collecting local environmental taxes for environmental governance, with the local tax bureau taking charge of the specific collection process. The taxpayers subjected to tax payment include enterprises, institutions, and individual businesses involved in the production, transportation, and other related activities that emit pollutants. In coordination with the local tax bureau, the local government designs reasonable collection standards and uses the local environmental tax for the locality’s fiscal budget and environmental needs. Along with the environmental tax, another vital environmental measure aimed at enterprises in China is the ‘pollutant discharge permit’ system. Enterprises must possess a discharge permit before conducting any emissions. The environmental protection authority at the city level where the enterprise is situated is responsible for issuing the discharge permit.

Overall, in the ‘inspection on government’ model, although the local environmental protection department serves as the implementation agency for environmental regulations, and its administrative management personnel is dispatched and financed by the local government, the local government can seemingly independently balance the relationship between economic development and environmental protection based on local industrial conditions. However, the stringent inspection mechanism established by the central MEE directly links the local environmental protection performance with the political responsibility of the local government. Local governments must devote much attention to the central government’s environmental policies and governance tasks to avoid being held accountable for political responsibility. They must also ensure that the adjustment of local industries and the implementation of environmental policies align with the central government’s plan.

Figure 1 Illustration of china's 'inspection on government' environmental governance system

2.2 Information and data collection

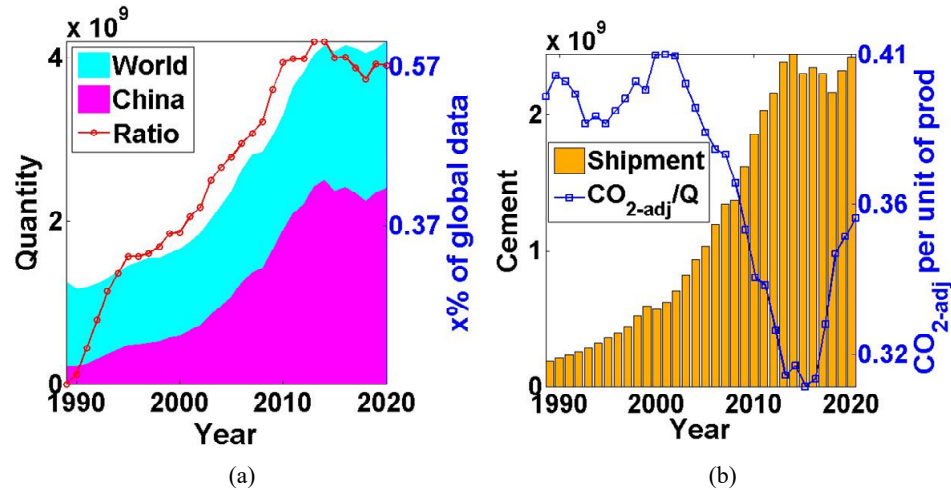
Data collection for this study encompassed annual cement output figures and market characteristics of China's cement industry from 1989 to 2020, sourced from the National Bureau of Statistics of China. This comprehensive dataset includes metrics such as annual shipment volume, export volume, average price, and foreign direct investment (FDI) in the construction sector. Central to the industry's operations is the process of crushing, grinding, and blending raw materials to form a homogenous mix; this methodical procedure is crucial for ensuring both operational efficiency and adherence to environmental standards. It is within this framework of structured processes that the cement industry demonstrates its market stability, evidenced by consistent production and sales patterns throughout the years (Tkachenko et al., 2023). Generally, most countries or regions report data on cement production, sales, and pricing annually (National Minerals Information Center, 2024; National Bureau of Statistics, 2023). However, in recent years, some regions have begun recording these indicators on smaller time scales. Nevertheless, these condensed data indicators expressed over the short term may not adequately meet the needs of long-term sample studies. To better reflect the overall development trend of the industry and the long-term changes under environmental supervision, we will study sample data spanning from the first year of the implementation of China's first official Environmental Protection Law in 1989 (Bao et al., 2021) to the previous year of the implementation of China's Ecological Environment Standard Management Measures in 2021 (Ministry of Ecology and Environment, 2020).

While, in the field of econometrics, researchers typically employ spatial panel models and expand the sample size of variables through a pattern of vector stacking (Lee et al., 2022). This operation indeed achieves a reduction in collinearity and an increase in degrees of freedom. However, spatial panel models are often more oriented towards examining the interactions between different regions and spatial dependencies within the data, rather than making numerical predictions under specific explanatory variables. In addition, one of the crucial objectives of this study is to employ machine learning methods after establishing a correlation model between variables, aiming to identify the optimal decision-making solution that aligns with the balance mechanism between the development of the cement industry and ecological conservation. Throughout this

process, numerical prediction and iterative computation are indispensable. Therefore, spatial panel model analysis is not applicable to advancing this study towards its goals. Although the sample size of 32 years of research is limited, as long as we analyse the fit of the model for variable associations, significance, significance of each explanatory variable, residual distribution, and residual autocorrelation meet expectations, such samples are sufficiently representative for elucidating the contribution relationship of explanatory variables to the explained variables (Jenkins and Quintana-Ascencio, 2020; Busico et al., 2020).

The annual cement output data of the world during the same period was taken from the ‘USA Geological Survey’ database. Amidst this epoch, both China and the rest of the world witnessed a surge in cement production (as shown in Figure 2(a)). China, the world’s leading cement producer, saw its production skyrocket from 210.29 million tons in 1989 to 2.39 billion tons in 2020, with an average annual growth rate of 8.16%. Similarly, the world’s cement production rose from 1.24892 billion tons in 1989 to 4.2 billion tons in 2020, with an average annual growth rate of 3.99%. Nevertheless, China’s share of global cement production wavered throughout this time. From 1989 to 1995, China’s proportion of cement production proliferated, followed by a brief three-year fluctuation before entering a second growth phase (the data corresponds to the right longitudinal axis in Figure 2(a)). By 2015, China’s share of cement production had dwindled gradually due to the further implementation of the country’s industry supply-side structural reform (Fuqian, 2023).

Figure 2 Illustration of china’s cement industry performance and adjusted CO_2 emissions per ton of cement production between 1989–2020 (a) output of cement (b) industry fundamentals in China (see online version for colours)



The data annual CO_2 emission from cement in China was collected from the online resource of the global carbon project (Ritchie et al., 2020). In comparison to researching the overall emissions of an industry, we are particularly interested in examining the amount of carbon dioxide emitted per unit of output. This metric could reflect a country’s progress towards developing a low-carbon economy, mitigating climate change, and iterating green technology efficiency (Petroche and Ramirez, 2022). The carbon dioxide

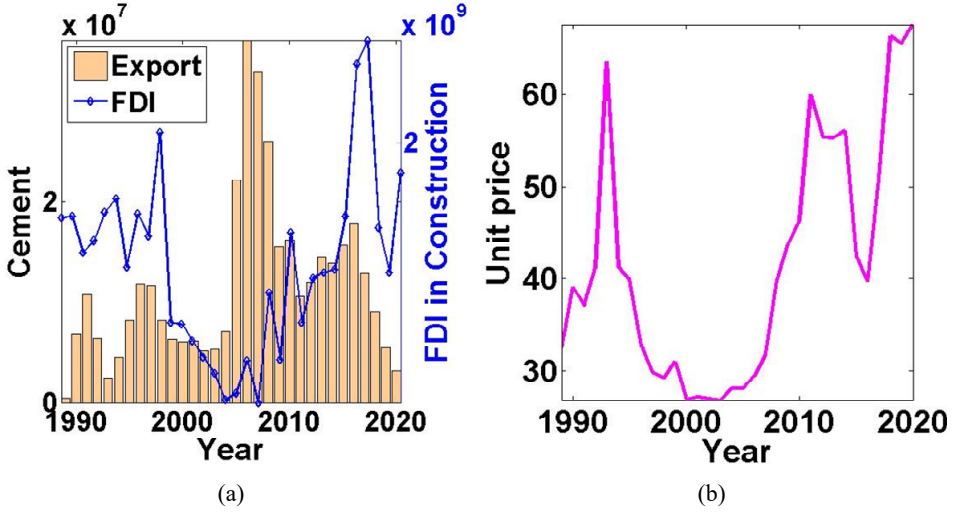
emissions data presented in this online database may appear lower in value when compared to figures disclosed in some academic literature (Ding, 2021), or government reports (United States Environmental Protection Agency (EPA), 2021) due to the adoption of a different weighted coefficient and estimation method rather than a simple average weighting model (Leffel et al., 2022). Despite these differences in calculation method and weighted coefficients, the carbon dioxide emissions data presented in this study remains an effective indicator for evaluating the ecological and environmental impacts resulting from the development of the cement industry. Therefore, to differentiate it from data generated using a simple average weighting model, this paper will use the term ‘adjusted CO_2 ’ (CO_{2-adj}) to refer to the emission data. Simultaneously, we are also highly concerned about the relationship between carbon reduction targets and industrial development, with the volume of shipment from mills being a critical indicator of industry growth in this study (Pascale and Greig, 2021). As illustrated in Figure 2(b), China’s cement shipment volume fluctuated similarly to production between 1989 and 2020, with an average annual growth rate of 8.6%. In contrast, the trend for CO_2 emissions per tonne of cement production in China generally declined (the curve corresponds to the data of right vertical axis in Figure 2(b)). This occurred as the country’s cement industry implemented green upgrades, leading to the adjusted CO_2 emissions per tonne of cement production reached their lowest point (0.31 tonnes) in 2015. However, there were instances of a rebound during this process, particularly after crossing the lowest value. Nevertheless, the strength of these rebounds has gradually diminished since 2018.

China’s cement export volume between 1989 and 2020 displayed a distinctive phased pattern of changes, as depicted in Figure 3(a). During the first phase (1989–2004), the export volume fluctuated somewhat but maintained an upward trend. Subsequently, the indicator demonstrated a sharp increase, reaching its peak in 2006 with an export volume of 36.13 million tons. However, as China’s cement export strategy entered its third stage in 2009, the growth trend reversed, and the export volume fell back to the level observed during the first phase.

Over the same period, the construction industry’s FDI, closely linked to the cement industry, has also undergone a phased fluctuation. Some studies provide evidence for the nonlinear changes in regional CO_2 concentration values directly caused by FDI inflows into emerging economies (Xie et al., 2020; Luo et al., 2022). In emerging economies, particularly in China, the relationship between the construction industry and the cement sector is highly intertwined, with the construction industry consistently ranking among the top recipients of foreign investment (Foreign Investment Administration, 2023). Therefore, in discussing the balance mechanism between cement industry development and ecological conservation, FDI in the construction industry will be an important explanatory variable.

Since 2000, FDI in the construction industry has entered a phase of periodic adjustment, with the investment amount showing a year-on-year decline and reaching its lowest value of 45,045.36 million dollars in 2004 (the data corresponds to the vertical axis in Figure 3(a)). Afterward, this indicator showed a fluctuating pattern of rebound. Figure 3(b) depicts the average mill value of cement per ton of cement in China over 32 years. After a gradual increase, China’s average ex-factory price of one ton of cement began to decline slowly in the mid-1990s, reaching its lowest point of 26.78 US dollars per ton. The indicator then started a slow rebound, but after 2012, it experienced a prolonged decline lasting until 2016 before gradually beginning to recover.

Figure 3 Illustration of export volume of china's cement industry, foreign direct investment in construction, and the average mill value of cement per ton between 1989–2020
 (a) cement export and FDI in construction (b) average mill value of cement (see online version for colours)



2.3 Industry agglomeration and environmental regulation stringency

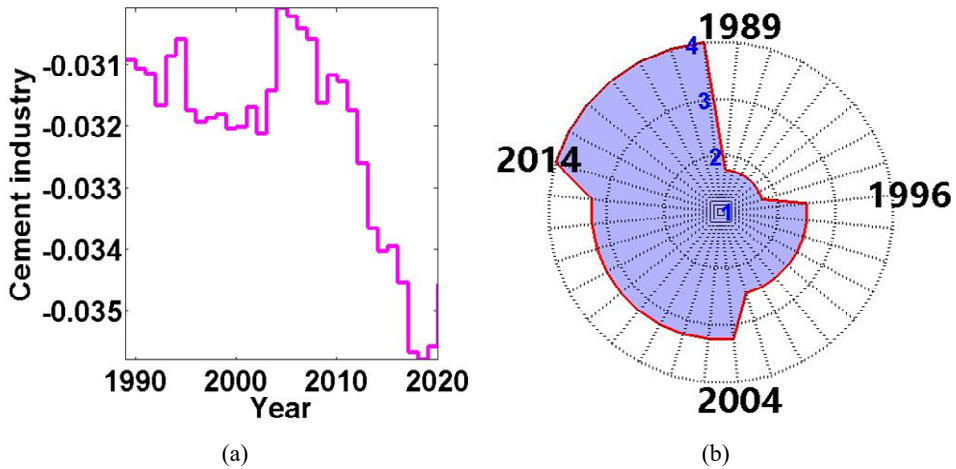
Scholars have long been interested in the spatial agglomeration effect of economic activities. In recent years, the increased availability of micro-level data and computing power has led to new measurement methods, providing researchers with more options when choosing different measures for empirical research (Nakamura and Paul, 2019). Compared to single indicators, the EG index can more comprehensively depict the complexity and diversity of industrial patterns. It possesses greater operational and guiding capabilities, enhancing the scientific accuracy of policy decision-making (Han et al., 2022). Thus, this study will utilise the EG index to depict the degree of agglomeration (Agg) in the Chinese cement industry. The relevant formula is outlined below:

$$Agg = \frac{G - \left(1 - \sum_{j=1}^m q_j^2\right)H}{\left(1 - \sum_{j=1}^m q_j^2\right)(1-H)} \quad (1)$$

In the formula above, $m \in N$ represents the total number of regions in the country, q_j indicates the proportion of industrial value added in region j relative to the country's total industrial value added. Furthermore, G denotes the spatial Gini coefficient of the Chinese cement industry, namely $G = \sum_{j=1}^m (S_j - q_j)^2$ where S_j is the proportion of cement production in region j relative to the total national cement production. In addition, $H = \left(\sum_{j=1}^m q_j (S_j / q_j)^2\right) / m$ denotes the relative form of the Herfindahl index, which provides an adequate reflection of the degree of competition within the industry. The EG

index values of China's cement industry have consistently been negative and exhibit an overall fluctuating decline from 1989 to 2020, as shown in Figure 4(a). This suggests that the industry has a low degree of agglomeration and is characterised by dispersion. However, this feature may benefit the industry's energy efficiency promotion (Tanaka and Managi, 2021).

Figure 4 Illustration of industry agglomeration and environmental regulation stringency of the cement industry in china between 1989–2020 (a) industry agglomeration (b) ER stringency, China (see online version for colours)



Undoubtedly, having an exact quantitative measure of environmental regulation stringency can assist governments in evaluating the effectiveness of their environmental management policies and developing or aligning more scientifically grounded and sustainable development strategies. There is no standardised quantitative measurement form for the stringency of environmental regulation. Some rely on a single criterion, such as emission standards (Yan et al., 2023), while others integrate multiple factors, including research and development subsidies, environmental taxes, pollutant emissions quotas, and energy trading schemes (Assamoi and Wang, 2023; Albulescu et al., 2022; Ghojogh et al., 2023). These measurement approaches have unique characteristics, providing governments with a range of options for decision-making from the perspective of cost reduction and coverage. However, research on individual industries needs to be more targeted than macro-level environmental research. Specifically, it is essential to avoid overly focusing on a single type of pollutant without a deep analysis of industry characteristics and to ensure that weight allocation of related factors are not overly subjective due to researcher bias. Such results may lead to vague generalisations, requiring other indicators to supplement evaluations, and can result in overestimation or underestimation of environmental regulations' pressure on industries.

This study defines the stringency of environmental regulation based on the 'emission standard of air pollutants for cement industry' implemented and revised in China between 1989 and 2020 (see Table A3). It integrates variable data from four dimensions, including the number of affected sources (e.g., rotary kiln, shaft kiln, dryer, etc.), the number of affected pollutants (e.g., dust, SO_2 , NO_x , fluoride, etc.), the fixed base growth rate (FBGR) of the number of improved emission limits for pollutants, and the FBGR of the

maximum improvement rate of emission limits. The variable matrix is simplified by the approach of the principal component analysis (PCA) (Ghojogh et al., 2023), retaining only the principal components with a contribution rate of no less than 80%, eventually forming a one-dimensional time-series vector of environmental regulation stringency (as shown in Figure 4(b)). Over 32 years, the ‘Emission standard of air pollutants for cement industry’ underwent three revisions in 1996, 2004, and 2014. Each of these revisions significantly increased the stringency of environmental regulation. The revisions made in 1996 and 2004 further highlighted the Chinese government’s emphasis on strengthening environmental regulations to address emerging environmental challenges and its determination to improve the environmental performance of the cement industry and promote sustainable development.

2.4 Stepwise multiple linear regression

Stepwise multiple linear regression (SMLR) is a statistical approach to quantify the relationship between an explained variable y and several explanatory variables x . The significance of existing regression terms in the linear combination will be tested each time a new term is added. If this term does not significantly improve the corresponding sum of squares of partial regression, it will be eliminated. This selection and exclusion process will be repeated until no further improvement can be achieved by introducing any new explanatory variables, and all variables included in the linear combination are regarded as necessary (Wang et al., 2023b). This study established a group of SMLR models (see equation (2)) to link the average CO₂ emissions per ton of cement and cement shipment with policy factors (industrial agglomeration, environmental regulation stringency) and market factors (export volume associated with the cement industry, FDI in construction, and the average mill price of cement per ton).

$$\begin{cases} y = b_0 + \sum_{i=1}^N b_i x_i + \sum_{i=1}^{N-1} \sum_{j=i+1}^N b_{ij} x_i x_j \\ + \sum_{i=1}^N b_i x_i^2 + \varepsilon_i, \varepsilon_i \sim N(0, \sigma^2), i = 1, 2, \dots, n \end{cases} \quad (2)$$

The model comprises N independent factors that explain the variations in the target function y , and each factor contains n observations. Furthermore, in equation (2), b_0 represents an arbitrary constant, b_i corresponds to the coefficients of each explanatory variable, and ε_i denotes the error term that follows a Gaussian distribution. The optimal model was selected based on the highest multiple correlation coefficient

$$\left(R^2 = \frac{\sum (\hat{y}_i - \bar{y})^2}{\sum (y_i - \bar{y})^2} \right) \text{ and the value of adjusting the R-squared } |$$

$(Adj-R^2 = 1 - (n-1)(1-R^2)/(n-N-1))$, which provides a more accurate measure of the proportion of variance explained by the model. Here, y_i and $\bar{y}$ represent the actual observation and its corresponding mean value, respectively. The model’s estimate is represented by $\hat{y}$. Moreover, the p-value of the overall F-test is also considered to assess the model’s performance, with smaller p-values indicating more accurate predictions. Additionally, if both R^2 and $Adj-R^2$ close to 1, and there is no significant gap between them, which indicates a well-performing model.

2.5 Genetic algorithms

GAs is an optimisation algorithms based on the principles of biological evolution, which simulates natural processes such as inheritance, mutation, and selection. It applies to search and solving methods to address problems (Katoch et al., 2021). The GAs' fundamental concept is to optimise by mimicking biological evolution. The solution to a problem is represented as chromosomes, with each chromosome made up of genes that represent decision variables. Genetic operations such as selection, crossover, and mutation can alter the composition of genes in chromosomes to evolve better solutions. Due to its ability to eliminate limitations such as target function differentiability and continuity while enabling independent exploration of multiple search points for optimal solutions, researchers frequently favour GAs in optimising emission reduction systems (Shin et al., 2019). Furthermore, De et al. utilised the GAs to explore the balance between corporate development and ecological protection under environmental regulations (De et al., 018). Their study aimed to explore the impact of government environmental regulations (such as carbon taxation and emissions trading schemes) on enterprises' economic and social performance by establishing a relevant model from a corporate perspective. Additionally, they utilised GAs to construct an optimal adjustment reference scheme for enterprises that optimises productivity and operating time while complying with environmental regulations to achieve maximum profit.

$$\max \phi(x) = \begin{cases} F[j(x)] = -j(x) \\ \begin{cases} a_{kj} = a_{ij}(1-b) + a_{ij}b \\ a_{lj} = a_{ij}(1-b) + a_{kj}b \end{cases} \\ a_{ij} = \begin{cases} a_{ij} + (a_{ij} - a_{max})f(g), \gamma \geq 0.5 \\ a_{ij} + (a_{min} - a_{ij})f(g), \gamma < 0.5 \end{cases} \end{cases} \quad (3)$$

This paper objects to determining the policy and market factors associated with maximising cement industry shipment under environmental constraints. Through this effort, we aim to identify the optimal combination of policy and market factors that balance ecological protection with industrial development, enabling the cement industry to maximise its shipment while complying with environmental constraints. To discretise the objective function and search for optimal solutions, we implemented real-coded GAs that utilise a simulated binary crossover (SBX) operator to perform crossover between two parent individuals and a parameter-based mutation operator to introduce diversity into the population. According to equation (3), our objective is to determine the maximum value of the interval function $\phi(x)$, where x represents a combination of explanatory variables related to cement industry shipment. These variables correspond to the actual values of binary codes from chromosome a_i in subsequent analyses that utilise GAs. In our case, the fitness function is defined as $F[\phi(x)]$, which is derived from the results of stepwise regression analysis. Since all individuals are encoded as real numbers, the corresponding crossover function can be determined based on the content presented in the second part of equation (3). Moreover, a_{kj} and a_{lj} correspond to the j^{th} gene of the k^{th} and l^{th} chromosomes at position j , respectively. In addition, b is a random number drawn from a uniform distribution in the interval $[0, 1]$. The third part of the equation (3) defines

the mutation function for the j^{th} gene of the i^{th} individual, where $a_{\max}$ and $a_{\min}$ represent the upper and lower limits of the gene value for individual a_{ij} . Furthermore, we use the function $f(g) = \gamma_2(1-g/G_{\max})^2$ to adjust the mutation rate concerning the current iteration (g) and the maximum number of evolutions ($G_{\max}$), which enhances the algorithm's performance. Note that γ is defined in the same way as b .

3 Statistical analysis and results

3.1 Regression analysis

Sabuj et al. highlighted two significant challenges the cement industry faces, high energy intensity and significant CO_2 emissions, which pose significant obstacles to industry advancement (Mandal, 2010). Nevertheless, implementing effective environmental regulations can positively impact the industry by improving regional energy efficiency and controlling undesirable outputs. As the empirical data utilised in this study was derived from India (whose regulatory framework is not 'inspection on government'), the impact of environmental regulation exhibits significant regional variation. Specifically, the study found that some states with geographic advantages can use imported coal with higher calorific values, significantly reducing their coal demand while maintaining adequate production levels. Meanwhile, other states with poor transportation infrastructure may only have access to domestic coal, limiting their options for reducing coal usage. In these cases, the effect of environmental regulations can often result from negotiations between enterprises and local environmental protection departments, leading to limited progress toward sustainable practices. However, when further discussing the specific positive impacts of environmental regulation, the study primarily emphasises the iterative upgrading of fuel selection by enterprises under the pressure of environmental regulatory policies without delving into the impact of such regulations on the industry's economic landscape. The study by Wang et al. (2021) provides further insights into this topic. Based on data from publicly traded Chinese cement companies between 2011 and 2019, they shed light on the adverse effects of environmental regulations on these companies' revenue and profitability. In particular, the study found that under the constraints of environmental regulations, a 10% increase in production capacity results in an average decrease in net profits and revenue of approximately 76 million RMB and 317 million RMB, respectively. While companies may be able to pass on the cost of environmental protection to consumers with relatively inelastic demand, the adverse effects of environmental regulations become more prominent in markets with high demand elasticity. It is important to note that unlike the 25-year window utilised by Mandal (2010) and Wang et al.'s (2021) research centres around the shorter-term window when the policy of 'heavy pollution weather emergency response' is implemented in China. While this methodology may offer insights into the immediate effects of specific environmental policies, it carries risks when evaluating the long-term effects of systematic environmental regulations on the industry using short-term data.

To accurately identify the optimal systematic policy design for balancing ecological protection and industrial development under the 'inspection on government' regulatory framework, mitigate the impact of unanticipated events on related outcomes, and improve our understanding of the influencing factors, our study focuses on a 32-year observation window between 1989 and 2020. This study focuses on two primary observation

variables that comprise the ‘balancing mechanism’: the green efficiency of industrial sectors (ζ), which represents the degree of decarbonisation within the industry and is reflected by the amount of carbon dioxide emissions per unit of cement output, and the shipment volume (η), which indicates the industry’s economic performance and is measured by annual cement shipment volumes (as shown in Appendix Table A1). Furthermore, this study analyses explanatory variables from two perspectives: policy and market control variables.

In our study, the policy and market control variables we have chosen show significant correlations with the iteration of green technologies (Ahmed, 2020; Xie and Teo, 2022). Moreover, the target variable of interest ζ inherently represents the iterations of green technology. To mitigate the issue of multicollinearity in the model, we did not introduce additional explained variables relevant to technology iteration.

Table 1 Summary statistics of the variables in the ‘balancing mechanism’ and its associated factors in China (1989–2020)

Variable	Percentile				
	Min	25 TH	50 TH	75 TH	Max
ζ	-1.8924	-0.7921	0.4649	0.7963	1.1428
η	-1.2115	-0.9375	-0.2713	1.1285	1.4619
x_1	-1.4816	-0.3794	0.3874	0.3874	1.3618
x_2	-2.1993	-0.5737	0.2785	0.6664	1.3036
x_3	-1.1162	-0.9044	-0.1408	0.8621	1.9555
x_4	-1.3506	-0.6624	-0.2167	0.4176	2.9603
x_5	-1.5405	-0.7566	-0.0313	0.5504	2.5205

Policy control variables primarily involve two indicators, environmental regulatory stringency (x_1) and industry agglomeration (x_2), as discussed in Section 2.3. For the Chinese cement industry, which operates under the regulatory framework of ‘inspection on government’, the authority of the decision-making role of the central government in determining and adjusting the policy control variables cannot be overstated (Wang et al., 2023a). Beyond policy control variables, certain market factors, including the average mill price of cement (x_3), export volume (x_4), and FDI in the construction industry (x_5), represent critical elements that impact changes in the ‘balancing mechanism’ (Mallagray et al., 2021; Xu et al., 2022). In our investigation, nominal indicators were predominantly employed to interpret the explanatory variables of economic indicators. This choice was driven by the primary objective of this paper, which is to assist policymakers in identifying policy and market factors influencing the green efficiency of the cement industry. Recent research findings suggest a more significant correlation between environmental issues and certain nominal economic indicators (Métais and Roger, 2022; Li and Xu, 2023). The numerical fluctuations of nominal indicators, which include the impact of inflation, will appear more pronounced, making them more likely to capture the attention of policymakers as explanatory variables. This heightened sensitivity will also prompt decision-makers to adapt more quickly to changes in the economic environment by balancing industrial development with ecological preservation mechanisms.

Section 2.3 shows significant differences in the order of magnitude among each variable’s raw time series data. In order to mitigate the impact of these differences on subsequent analysis, we have standardised all the data (as shown in Table 1).

Before discussing the regression model, it is necessary to analyse the linear correlation of variables and perform a collinearity diagnosis to ensure that all explanatory variables are linearly independent (Zhai et al., 2018). Table 2 shows the correlation coefficient matrix among all explanatory variables. It is generally believed that there is no multicollinearity between variables when the correlation coefficient is less than 0.7. Therefore, according to the description in Table 2, the explanatory variables are all free from multicollinearity. However, for the sake of rigor, we also introduced variance inflation factors (VIF) to help diagnose whether there is collinearity among the explanatory variables. In our study case, the VIF values corresponding to the explanatory variables are 3.9516, 4.9142, 1.6582, 1.8792, and 1.7754, respectively, which satisfy the premise of no or weak collinearity.

Table 2 Correlation matrix of explanatory variables

	x_1	x_2	x_3	x_4	x_5
x_1	1				
x_2	-0.6732	1			
x_3	0.4059	-0.6218	1		
x_4	0.3874	0.1446	-0.171	1	
x_5	0.0892	-0.5384	0.3574	-0.249	1

We will import all explanatory variable sequences into equation (2) for in-depth analysis in the following steps. Specifically, we will utilise the method of multivariate stepwise regression to examine the influential factors of the dependent variables ξ and η individually. This process will involve the selection of variables based on a significance level of 95%. Furthermore, the exploration yields the following regression equation for the green efficiency of industrial sectors (ξ).

$$\xi(x) = 0.3149x_3^2 - 0.6475x_3 - 0.6041x_1 + 0.3677x_2x_4 - 0.3051x_4 - 0.3566 \quad (4)$$

and the regression equation for the shipment volume (η)

$$\eta(x) = -0.2586x_3^2 + 0.5657x_3 + 0.1425x_5^2 + (0.2248x_1 + 0.2445x_2 - 0.2144)x_5 + 0.7661x_1 + 0.2205 \quad (5)$$

Figure 5 provides a visual comparison between the original observed data and the regression-fitted data for both the green efficiency of industrial sectors and the shipment volume. Notably, the regression curves for both dependent variables aptly depict the overall trend of the observed data's fluctuations. In the case of equation (4), the observed R^2 stands at 0.9285 with an adjusted R^2 of 0.9147, accompanied by a remarkably low p-value of 4.674×10^{-14} . Conversely, for equation (5), the observed R^2 and $Adj-R^2$ demonstrate higher values of 0.9665 and 0.9568, respectively, while yielding an impressively low p-value of 3.8325×10^{-16} . Thus, based on these results, it can be affirmed that the explanatory variables in both regression models are notably significant. In the diagnosis of regression models, the Durbin-Watson test can help assess the independence between residuals and independent variables (Kim, 2022). The values of the Durbin-Watson statistic obtained from both models fall clearly within the range of 1.5 to 2.5. This strongly suggests that, at a 1% significance level, we cannot reject the null hypothesis of no residual autocorrelation (Atıcı et al., 2020). Hence, we can infer that

there is evidence supporting the independence between residuals and independent variables.

Figure 5 Illustration of original data and regression results for the green efficiency of the industrial sector of cement, china, and the shipment volume, respectively (a) original data and regression result of CO_{2-adj}/Q (b) original data and regression result of shipment (see online version for colours)

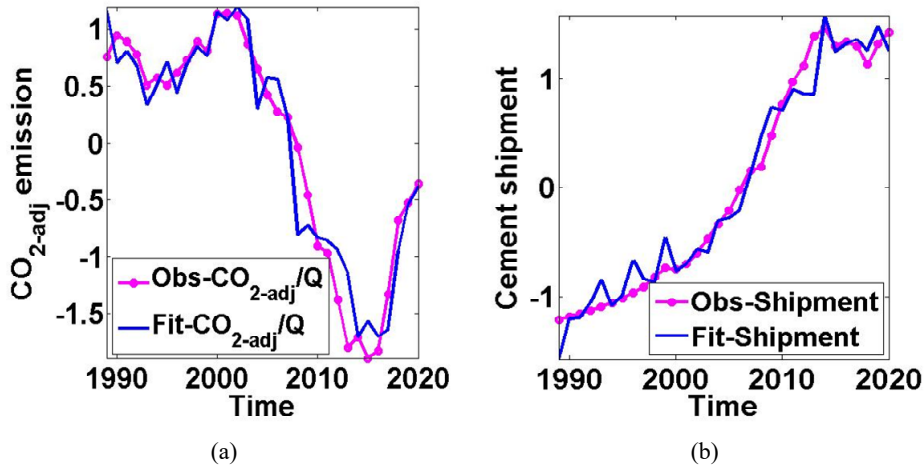
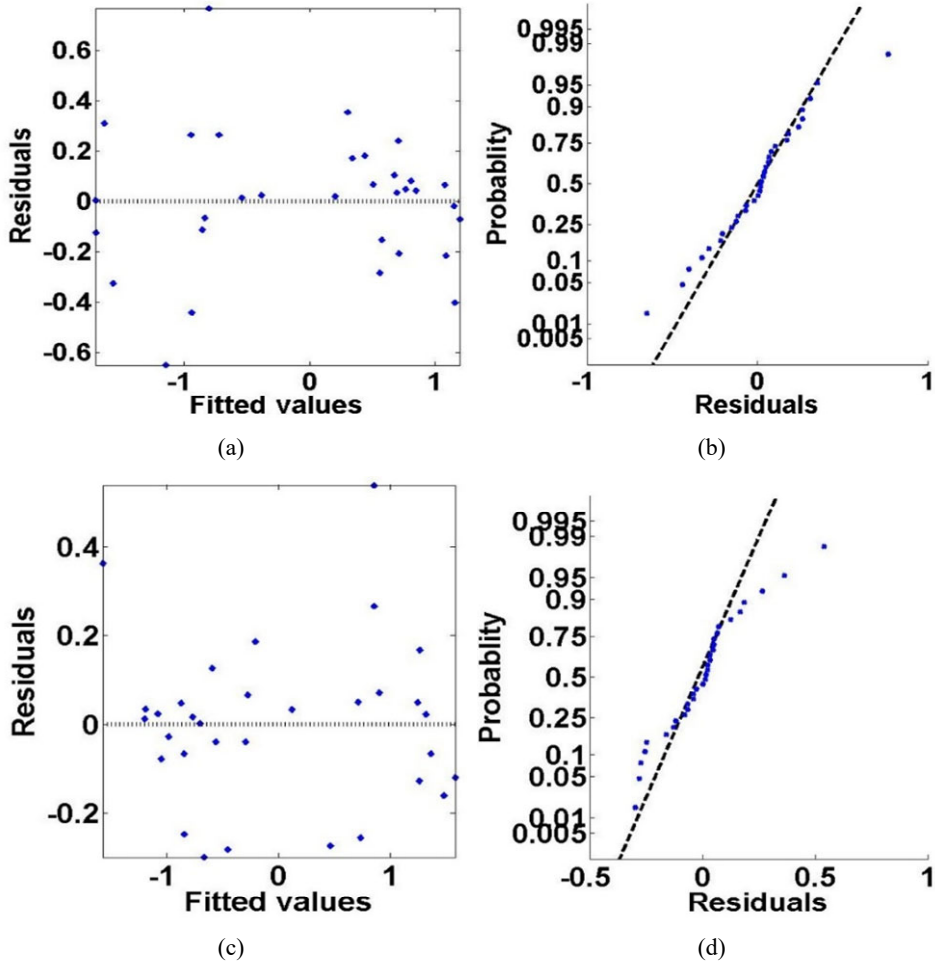


Figure 6(a) and Figure 6(c) showcase the association between the regression residuals and fitted values corresponding to the variables ‘the green efficiency of industrial sectors’ and ‘the shipment volume’ within models (4) and (5), respectively. The horizontal axis in the figures represents the fitted values, while the vertical axis represents the regression residuals. It is apparent that most of the residuals are distributed within a consistently uniform band. Hence, it can be concluded that the residuals for each regression equation largely adhere to the assumption of homoscedasticity. Two plots on the right-hand side of Figure 6 present the normal probability distribution of the residuals for each model. Notably, with only a few exceptions as outliers, most residuals closely adhere to the reference line. This observation suggests that the residuals in both regression equations exhibit substantial conformity to a normal distribution.

Figure 6(a) and Figure 6(c) showcase the association between the regression residuals and fitted values corresponding to the variables ‘the green efficiency of industrial sectors’ and ‘the shipment volume’ within models (4) and (5), respectively. The horizontal axis in the figures represents the fitted values, while the vertical axis represents the regression residuals. It is apparent that most of the residuals are distributed within a consistently uniform band. Hence, it can be concluded that the residuals for each regression equation largely adhere to the assumption of homoscedasticity. Two plots on the right-hand side of Figure 6 present the normal probability distribution of the residuals for each model. Notably, with only a few exceptions as outliers, most residuals closely adhere to the reference line. This observation suggests that the residuals in both regression equations exhibit substantial conformity to a normal distribution.

Figure 6 Illustration of the relationship between the regression residuals and the fitted values and the corresponding normal probability plots of the residuals (a) residuals analysis, $CO_2\text{-adj}/Q$ (b) norm-prob plot of residuals, $CO_2\text{-adj}/Q$ (see online version for colours)



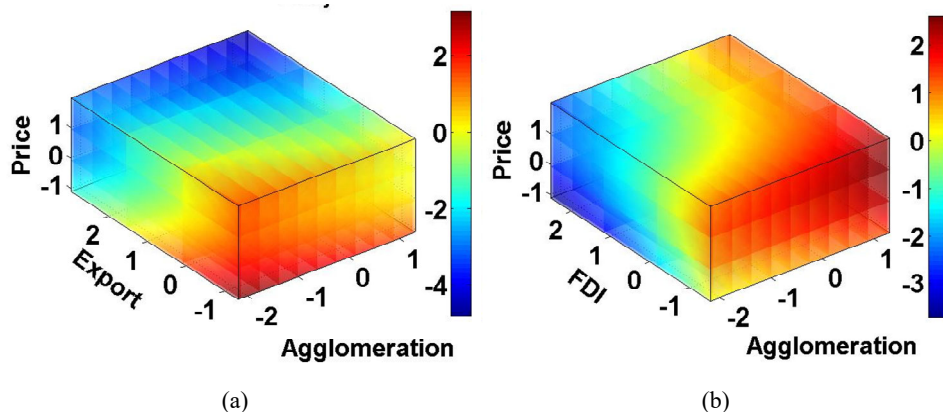
Note: The content refers to the green efficiency of the industrial sector of cement in china described in (a)–(b) in (c)–(d), the details are relevant to the shipment volume.

3.2 Sensitive analysis under stringent environmental regulation

The coefficient associated with environmental regulatory stringency (x_1) is -0.6041 in equation (4), which signifies that every 10% increase in x_1 , ξ will decrease by approximately 6.041%. However, the relationship in equation (5) between environmental regulatory stringency and its effects is not transparent. This is primarily because the coefficient linked to x_1 is not a fixed constant but rather represented as $0.7661 + 0.2248 x_5$. Despite this, we can still infer from the contents of Table 1 that the coefficient associated with the x_1 in equation (5) is positive. From a long-term perspective, the reinforcement of environmental regulatory stringency has not posed any obstacles to the

growth of shipment volume in the cement industry. Contrarily, based on the components of equation (5), it can be seen that for China's cement industry

Figure 7 Illustration of the influence of control variables on carbon dioxide emissions per unit of cement production and the growth of shipment volume in the cement industry at the maximum value of x_1 within its historical fluctuation range (a) cement CO_2 -adj/Q, China (b) cement shipment, China (see online version for colours)



the iteration of environmental regulatory stringency can also play a positive role in curbing the decline in cement shipment volume caused by fluctuations in the average mill price of cement and construction industry FDI. In order to enhance comprehension regarding the influence of market control variables on carbon dioxide emissions per unit of cement production and the growth of shipment volume in the cement industry, particularly when environmental regulations become much more stringent, we have devised a series of matrices for each of the two explanatory variables. These matrices illustrate the outcomes resulting from such changes within the context of historical data on industrial agglomeration fluctuations. For further details, please refer to Figure 7. From equations (4) and (5), it becomes evident that the factors influencing each explanatory variable consist of the policy and market control variables mentioned in our analysis. If we were to analyse the range of historical data changes for each variable separately, it would not only introduce substantial computational complexity but also prove ineffective in advancing our exploration.

In order to maintain the relevance of the discussion and enhance the accuracy of predicting short-term development trends, the matrix illustrating the outcomes of variables' changes will be established based on fixing the environmental regulatory stringency at the maximum value within its historical fluctuation range (i.e., $x_1 = 1.3618$). Given that our observation covers 32 years and all data is calculated annually, we have chosen a matrix size of $32 \times 32 \times 32$ in Figure 7 to provide a visual illustration. In this depiction, different colours are utilised to indicate the corresponding value levels of the explained variable. One notable finding in Figure 7(a) is that as the volume of cement exports decreases, the effectiveness of adjusting policy control variables in mitigating the growth of carbon dioxide emissions per unit of cement production diminishes gradually. In the face of shrinking overseas demand markets, ensuring cost control efficiency undoubtedly becomes the utmost concern for the entire industry. As pressure mounts, maintaining investments in carbon reduction innovation within the industry will

inevitably face obstacles, presenting challenges to the industry's overall green upgrading objectives in such an environment. Moreover, Tanaka's study highlights the inherent difficulties in leveraging the agglomeration effects to pose challenges to raising energy efficiency due to geographical constraints on raw materials faced by the cement industry (Tanaka and Managi, 2021).

Undoubtedly, promoting the formation of a dispersed structure in the cement industry through moderate government intervention holds the potential for realising energy conservation and emission reduction goals. However, it is worth noting that the study does not offer conclusive evidence on whether a sustained reduction in industrial agglomeration after establishing a dispersed pattern is conducive to the industry's overall development. Based on our evidence at hand, it is apparent that once the dispersed pattern is formed within the industry and the most stringent environmental regulations remain in effect, encouraging further reduction in industrial agglomeration yields positive outcomes in terms of reducing carbon dioxide emissions per unit of cement production only when the cement export volume exceeds the average level of the observed data window, as supported by the data provided in Table A4.

On the other hand, as environmental regulations become much more stringent, there is a discernible change in FDI in the construction industry tends to shift gradually from supporting the production and transportation of conventional building materials towards optimising the industrial product structure, developing and promoting low-carbon technologies for building materials and enhancing the recycling rate of construction waste (Zhao and Wang, 2021). Policy constraints, competition from recycled alternatives, and evolving market expectations for low-carbon products will pressure the concept shipment volume. Based on the evidence we have gathered (as depicted in Figure 7(b)), it is evident that in cases where agglomeration levels are low, the increase in FDI in the construction industry has a more pronounced compressive effect on the supply volume of cement. As evident from Table A5, the cement shipment volume values corresponding to the matrix with the lowest degree of aggregation ($x_2 = -2.1993$) are consistently lower than those observed in cases where the degree of aggregation approximately aligns with the average level of data within the observation window or reaches the highest value. Stricter environmental regulations have continuously enhanced the foreign investment environment and accelerated the elimination of dispersed obsolete production capacity and equipment. It is crucial to highlight that, both ξ and η demonstrate significant nonlinear effects within the model. The subsequent section will thoroughly examine the analytical constraints arising from these high-dimensional nonlinear variables in the context of balancing ecological protection and industrial development.

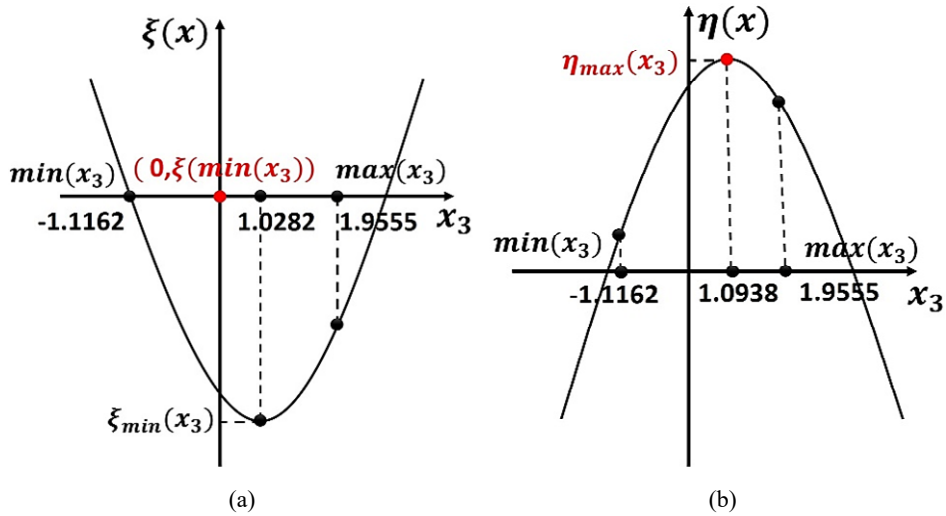
4 Optimal decision rule for balancing decarbonisation and development

4.1 Decarbonisation target and prerequisites for achievement

In the upcoming discussion, our primary objective is to explore how, while reducing carbon dioxide emissions, we can achieve maximum improvement in shipment volume corresponding to different price levels within the historical fluctuation range. This will be accomplished by strategically defining the intensity of environmental regulations and industrial agglomeration, considering various values of export volume and FDI in the construction industry. We aim to optimise the effects and maximise the potential for

increasing shipment volume by aligning these factors. As the Paris Agreement outlines, the 2°C scenario (2DS) requires reducing carbon dioxide emissions to approximately 520–524 kg per ton of cement produced (Ding, 2021; IEA, 2018). However, the current data for the cement industry in China shows an average emission of around 616.6 kg per ton (Ding, 2021). As illustrated in Section 2.2, it is essential to note that variations exist between the CO₂ emission data mentioned in the agreement and the data employed in this study due to variations in calculation weights. In order to facilitate further exploration, we will utilise a relative indicator, denoted as α , to quantify the extent of carbon reduction. This indicator will be defined as the target reduction ratio. By adopting the most stringent emission standards mentioned in Ding (2021), IEA (2018), we can obtain $\alpha = 520.0 \text{ kg}/616.6 \text{ kg} \approx 0.8433$. To establish the emission reduction baseline $\bar{C}$ in this study, we employ the mean value derived from the proportion of carbon dioxide (CO_{2-adj}) data with cement production data during the final five years of the observation window (2016–2020, aligning with China's thirteenth five-year plan construction period (Wan et al., 2022)), and hence $\bar{C} = 0.3384$. Additionally, we determine κ as the standardised desired level of carbon dioxide emissions per ton of cement. After conducting the necessary calculations, κ is given by -2.4973 .

Figure 8 Illustration of the evolution trends for the variables ξ and η as the fluctuation of the value of the average mill price of cement (a) $\xi(x)$ vs. x_3 (b) $\eta(x)$ vs. x_3 (see online version for colours)



Referring to equation (4), it becomes apparent that a quadratic function concerning the cement price x_3 can represent the carbon dioxide emissions per ton of cement (see Figure 8(a)). By analysing the nature of this function, it becomes evident that the maximum value is achieved at $\min(x_3) = 1.0282$. Hence, we can conclude that

$$\xi(\min(x_3)) = 0.7585 - 0.6041x_1 + (0.3677x_2 - 0.3051)x_4 \quad (6)$$

Under the emission reduction goal, our objective is to ensure $\xi(\min(x_3)) \leq \kappa = -2.4973$, thereby maintaining the average carbon dioxide emissions per ton of cement below κ

throughout the historical price fluctuation range. It is evident from equation (6) that there exists an inverse relationship between the environmental regulation intensity x_1 and the carbon dioxide emissions per ton of cement. To successfully achieve the decarbonisation target, it is crucial to ensure $x_1 \geq 5.3898 + x_4$ ($0.6087x_2 - 0.5051$). As we proceed, two pivotal issues demand thorough contemplation. First and foremost, when x_4 (overseas market demand) varies within its historical range, which intervals allow us to effectively lower the ‘average carbon dioxide emissions per ton of cement to the level κ , or potentially even lower, by adjusting the level of industrial agglomeration (x_2) irrespective of the fluctuations in the historical average mill price range of cement. It is essential to highlight that China’s environmental regulation operates under a system where central agencies are entrusted with oversight, and local government officials are held accountable. This approach, which directly impacts the performance assessment of local officials, often results in local businesses being obligated to comply with the most stringent environmental regulatory demands (Yang and Xue, 2016). As early as 2014, China’s environmental regulation intensity x_1 had reached its highest point based on historical data since 1989. By the conclusion of China’s thirteenth five-year plan in 2020, most cement companies in China had completed equipment upgrades to meet the demands of the most rigorous environmental regulations at that time (Guo et al., 2022). As a result, even if the future carbon reduction targets require a decrease in the necessary environmental regulation intensity, the industry would not need extensive technological iterations or equipment adjustments. The required environmental regulation intensity changes to meet the carbon reduction goals would have minimal impact on compliance costs. Therefore, it is still preferable to persist with the original approach of managing the industry based on the highest environmental regulation intensity. This strategy avoids imposing additional burdens on industrial development and ensures a robust safeguard for sustaining the stable outcomes of carbon reduction throughout the entire industry.

Another issue pertains to identifying the range of values for x_4 , where solely adjusting the level of industrial agglomeration (x_2) while maintaining the existing environmental regulation intensity would not be enough to achieve the desired objectives. In such cases, it becomes crucial to exceed the historical upper limit of x_1 . Equations (4) and (5) suggest that within the historical data range of x_4 and x_5 , elevating x_1 holds significant benefits in reducing carbon dioxide emissions and boosting cement shipment volume. It is worth noting that recent research findings (Yi and Liu, 2022) have emphasised that with proper timing of environmental regulation implementation, even when cement enterprises invest in compliance technologies and environmental facilities to meet market access requirements, the incurred compliance costs can be offset by the net returns from industry asset appreciation. This indicates that stricter environmental regulations can facilitate industry upgrading by ensuring stable shipment volume.

Regarding the constraints on the environmental regulatory intensity and industrial agglomeration level as discussed earlier, we can infer that the above two problems are contingent upon the following premises

$$5.3898 + (0.6087x_2 - 0.5051)x_4 \leq \max(x_1) = 1.3618 \quad (7)$$

$$5.3898 + (0.6087x_2 - 0.5051)x_4 > \max(x_1) = 1.3618 \quad (8)$$

Based on this, two scenarios can occur for the product of x_2 and x_4 to meet or fall below the threshold of -4.028 . Firstly, x_4 must be negative, while $0.6087x_2 - 0.5051$ is positive.

However, within the standardised historical value ranges of $x_2 \in [-2.1993, 1.3036]$ and $x_4 \in [-1.3506, 2.9603]$, even if we minimise x_4 and maximise $0.6087x_2 - 0.5051$ (when $x_2 = 1.3036$ and $x_4 = -1.3506$), the resulting value is only -0.3896 , which is still greater than -4.028 . Therefore, this ‘possibility’ does not hold.

Considering the second possibility ($x_4 > 0$ and $0.6087x_2 - 0.5051 < 0$, i.e., $x_2 < 0.8297$), we rearrange the corresponding equation to obtain $x_2 \leq 0.8297 - 6.6171/x_4$. If there is an overlap between the derived condition and the normalised historical values of x_2 , then it indicates that $0.8297 - 6.6171/x_4 \geq -2.1993$, s.t. $x_4 \geq 2.1846$. For the condition to be valid across the historical fluctuation range of standardised values for x_2 and x_4 , x_2 should lie within the interval $[-2.1993, 0.8297 - 6.6171/x_4]$, while x_4 should fall within $[2.1846, 2.9603]$. Under this premise, the environmental regulatory intensity that satisfies the carbon reduction requirements can be set within the interval $x_1 \in [5.3898 + (0.6087x_2 - 0.5051)x_4, 1.3618]$. Furthermore, considering equation (8), after simplification, we have $(0.6087x_2 - 0.5051)x_4 > -4.028$. The two inequalities we’ve analysed are complementary in nature. When the condition defined by the first inequality is not met, the second inequality naturally applies. This transition occurs under specific conditions, namely

$$\text{a} \quad \text{when } x_4 \in [2.1846, 2.9603], \text{ and } x_2 \in \left[0.8297 - \frac{6.6171}{Exp}, 1.3036 \right]$$

$$\text{b} \quad \text{when } x_4 \in [-1.3506, 2.1846], x_2 \in [-2.1993, 1.3036].$$

when $x_4 \in [2.1846, 2.9603]$, we have already found a solution that can reduce the average carbon dioxide emissions per ton of cement to a level κ or even below without exceeding the existing environmental regulatory intensity. Hence, we will no longer consider more expensive options and only consider the second scenario where it is necessary to surpass the historical upper limit of x_1 in order to achieve the carbon reduction goal. It is essential to notice that proposing higher intensity requirements on top of existing environmental regulatory standards introduces more significant uncertainty regarding the optimal timing for implementing such stringent regulations. The compliance cost range, fluctuations in the value of the industry’s underlying assets, and unexpected events that can impact asset values (such as economic changes or abnormal pricing of imported foreign products affecting the market) continuously arise as unfavourable factors in determining the optimal timing for implementing environmental regulations and controlling the costs of industrial green transformation. In addition, due to market characteristics within the cement industry, companies generally face challenges in promptly passing these increased compliance costs to downstream markets. Consequently, this may weaken environmental regulations’ driving force toward industry upgrading (Wang et al., 2021). Undoubtedly, the environmental regulatory intensity x_1 functions like a strong rope with the power to curtail carbon dioxide emissions in any industry. However, it is straightforward that when the design of x_1 is compelled to exceed historical upper limits, a cautious choice of the minimum regulatory intensity that aligns intending to reduce carbon dioxide emissions will be more helpful in mitigating the negative impacts of uncertainty on industrial development. According to equation (8), the appropriate approach is to set the environmental regulatory intensity at $x_1 = 5.3898 + (0.6087x_2 - 0.5051)x_4$.

4.2 Optimal decision model on main assumptions

Clearly, within the fluctuation range of historical data, both the government and companies in the industry desire larger cement shipments corresponding to each price. The cement shipment volume function, denoted as η , is also a quadratic function of the average mill price of cement (x_3). The degree of curvature in this function depends on the absolute value of the highest coefficient of the quadratic term concerning x_3 , which is 0.2586 (Ellis and Grinstead, 2008). Since the coefficient of the linear term is also known, the position of the inflection point of this function can be determined. Moreover, it can be observed that in the two-dimensional plane, the basic shape of this curve remains constant, while variations in x_1 and x_2 values merely cause the downward-curving curve to move vertically along the central axis at $x_3 = -(0.5657)/(-0.2586 \times 2) = 1.0938$.

Based on the definition of environmental regulatory efficiency in Section 1, our objective is to identify the most appropriate policy combination design that balances environmental protection and industrial development. Specifically, we aim to maximise shipment volumes for each value within the historical fluctuation range of prices. From

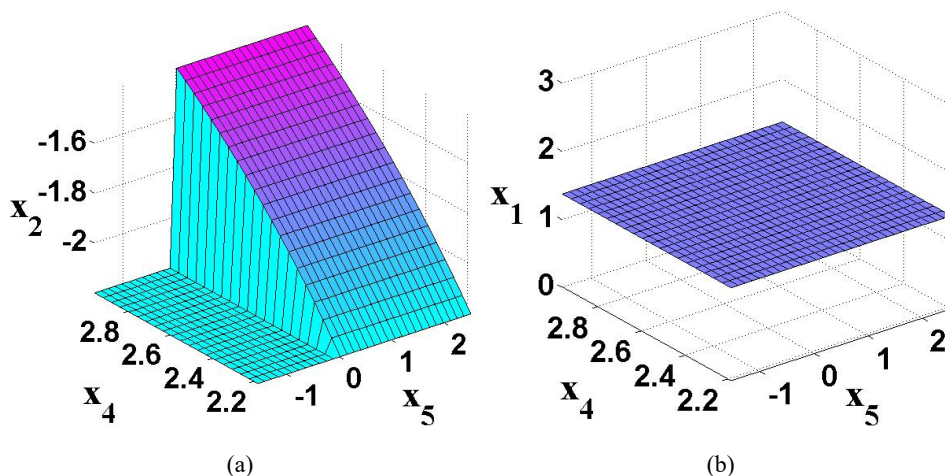
$$\begin{aligned} \max[\phi(x)] &= 0.1425x_5^2 + (0.2248x_1 + 0.2445x_2 - 0.2144)x_5 + 0.7661x_1 + 0.5299 \\ \text{s.t.} \left\{ \begin{aligned} &5.3898 + (0.6087x_2 - 0.5051)x_4 \leq x_1 \leq 1.3618 \\ &-2.1993 \leq x_2 \leq 0.8297 - 6.6171/x_4 \\ &2.1846 \leq x_4 \leq 2.9603 \\ &-1.5405 \leq x_5 \leq 2.5205 \end{aligned} \right. \quad (9) \end{aligned}$$

the geometric properties of function (5), it becomes clear that to fulfill these criteria, we need to push the curve upward along the central axis as much as possible, striving to find the optimal conditions where the vertex of $\eta(x)$ is maximised. Drawing upon the findings in Section 4.1 and considering the suggested value for the vertex of the quadratic function concerning x_3 in equation (5), we can determine the optimal function ($\max(\phi_1(x))$) that meets the carbon reduction objective while staying within the limits of the existing environmental regulatory intensity.

It is evident that the objective of function (9), with multiple constraint conditions, is to search for optimal parameters on a quadratic function relating to x_5 . These quadratic functions open upward, and their inflection point's position is solely determined by the constraints on x_1 and x_2 . Considering the variable constraint conditions mentioned in equation (9), we can infer that the inflection point's position range lies between [0.8839, 2.6931]. It is evident that within the historical data interval of $x_5 \in [-1.5405, 2.5205]$, the minimum value is even farther away from the inflection point's position. This signifies that $x_5 = -1.5405$ is one of the optimal conditions for function (9). Furthermore, due to the uncertainty in the coefficient terms associated with policy control variables x_1 and x_2 in $\max(\phi_1(x))$, which is solely correlated with the known range of variable x_5 , it becomes apparent that $x_1 = 1.3618$ (maximum in historical data) and $x_2 = -2.1993$ (minimum value in historical data) are the remaining optimal conditions for equation (9). By substituting these values into the objective function (9), the optimal result obtained is $\max(\phi_1(x)) = 2.5984$. From the optimal variable selection corresponding to function (9), when the normalised export volume $x_4 \in [2.1846, 2.9603]$, it can be observed that for China's cement industry, implementing the strictest environmental regulations and maintaining the lowest level of industrial agglomeration are crucial conditions for achieving both

carbon reduction targets and maximising cement shipment. Simultaneously, suppressing FDI in the construction industry until its historical data reaches a minimum level is also necessary.

Figure 9 Illustration of the optimal policy control variables in response to variations in the market control variables as $x_4 \in [2.1846, 2.9603]$, $x_5 \in [-1.5405, 2.5205]$ for achieving both carbon reduction targets and maximising $\eta(x)$ (a) optimal degree of agglomeration (b) optimal intensity of ER (see online version for colours)

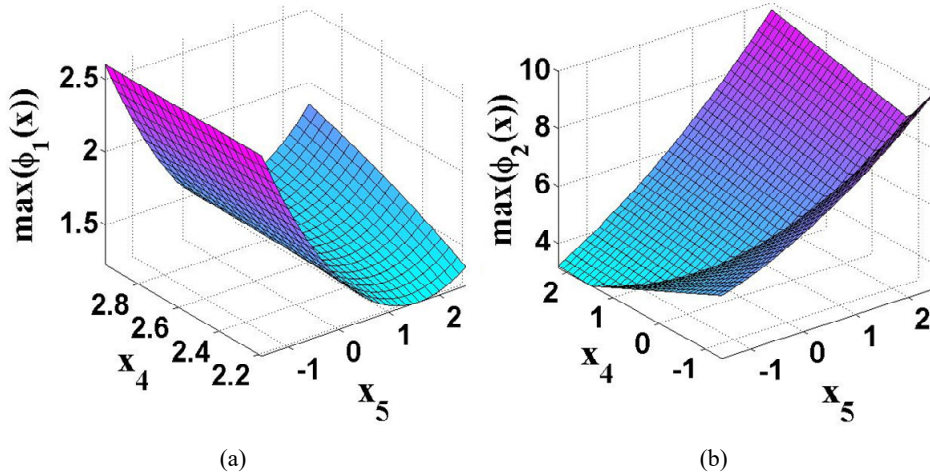


It is crucial to highlight that in regions where the primary environmental regulatory approach is ‘supervision and governance,’ policy guidance plays a critical role in shaping policy control variables (x_1 and x_2). However, when it comes to market control variables (x_4 and x_5), policy stimulation can only have a limited impact on adjustments. Therefore, this study requires careful consideration to explore how modifications in policy control variables (x_1 and x_2) can effectively achieve carbon reduction targets and maximise $\eta(x)$. It is essential to consider the historical fluctuations of market control variables (x_4 and x_5) while undertaking this analysis. From equation (9), it is evident that the positive or negative trend of variable x_5 determines whether the industrial agglomeration, represented by the variable x_1 , promotes or inhibits cement shipment. As shown in Figure 9(a), when x_5 is negative, the optimal decision is to maintain the minimum industrial agglomeration level. However, as x_5 approaches positive values and gradually increases, strategies to enhance shipment must include significantly strengthening the industrial agglomeration level, given by $x_2 = 0.8297 - 6.6171/x_4$. Furthermore, in such cases, the larger the export volume, the higher the required level of agglomeration for the optimal decision. On the other hand, equation (9) also clearly states that regardless of the level of x_5 , the coefficient of the variable x_1 remains positive. Therefore, within the range $x_4 \in [2.1846, 2.9603]$ and $x_5 \in [-1.5405, 2.5205]$, maintaining the most stringent environmental regulations holds a significant positive impact on maximising shipment (as shown in Figure 9(b)).

Overall, based on the optimal conditions of policy control variables, $\max(\phi_1(x))$ exhibits a U-shaped relationship in the x_5 dimension, as shown in Figure 10(a). When x_5 is less than 0 and tends towards lower values, $\max(\phi_1(x))$ increases to its maximum value gradually, and it aligns with the determination of the optimal parameters for $\max(\phi_1(x))$.

Due to the given circumstances, $\max(\phi_1(x))$ is independent of x_4 . Therefore, when policy control variables ($x_1 = 1.3618$, $x_2 = -2.1993$, and the market control variable $x_5 = -1.5405$ are set, regardless of the level of x_4 within the range $[2.1846, 2.9603]$, the shipment levels corresponding to each price are higher than those of other parameter combinations within the historical data range. When $x_5 > 0$, the values of x_4 has been taken into account for determining the optimal parameter of x_2 . As a result, the $\max(\phi_1(x))$ values, corresponding to different levels of x_4 , form multiple parabolas with upward openings and distinct inflection points. Figure 10(a) illustrates that at the same level of x_5 , a higher quantity of output leads to more significant shipments while still meeting the carbon reduction requirement. This observation highlights the positive relationship between output quantity and shipment achievement within the constraints.

Figure 10 Illustration of the optimal value of maximising $\eta(x)$ that meets the carbon reduction objective while (a) $x_4 \in [2.0846, 2.9603]$, $x_5 \in [-1.5405, 2.5205]$ and (b) $x_4 \in [-1.3506, 2.1846]$ and $x_5 \in [-1.5405, 2.5205]$ (see online version for colours)



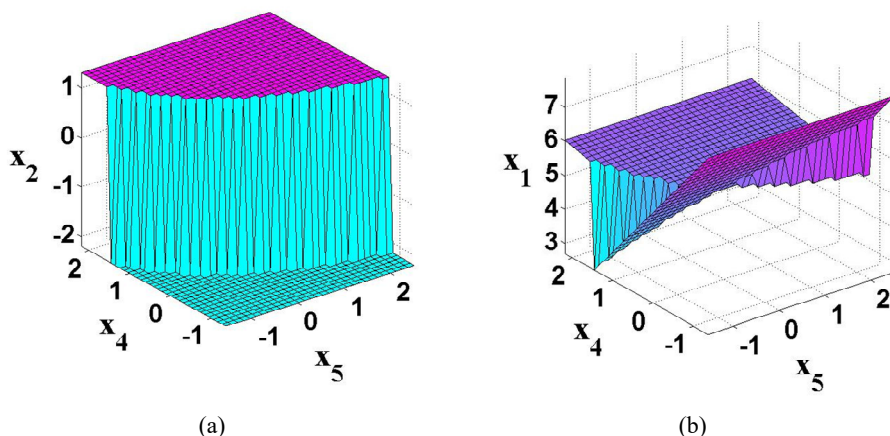
Next, we will discuss the optimisation problem of cement shipment volume by breaking through the historical limit of x_1 to help achieve carbon reduction targets. According to the conclusion in Section 4.1, in order to effectively mitigate the uncertainty brought by increased environmental regulations and their negative impact on industrial development, the value of x_1 will be controlled at $5.3898 + (0.6087x_2 - 0.5051)x_4$. The optimal function under this scenario ($\max(\phi_2(x))$) can be derived by substituting this conclusion into equation (5)

$$\begin{aligned} \max(\phi_2(x)) &= [0.4663x_4 + (0.1369x_4 + 0.2445)x_5]x_2 + 0.1425x_5^2 \\ &\quad - (0.1135x_4 - 0.9974)x_5 - 0.3869x_4 + 4.659 \\ \text{s.t. } &\begin{cases} -2.1993 \leq x_2 \leq 1.3036 \\ -1.3506 \leq x_4 \leq 2.1846 \\ -1.5405 \leq x_5 \leq 2.5205 \end{cases} \end{aligned} \quad (10)$$

In order to determine the optimal combination of explanatory variables within their respective ranges for maximising the objective function (10) subject to multiple constraints, we utilised the GAs as described in Section 2.5. The convergence computation yielded a maximum value of 10.0418 for $\phi_2(x)$. Correspondingly, the market control variables were found to be $x_4 = -1.3506$ (minimum historical data value) and $x_5 = 2.5205$ (maximum historical data value). The policy control variables were determined to be $x_1 = 7.88$ and $x_2 = -2.1993$. While meeting the constraints, the maximisation of cement shipment highly depends on objective conditions such as the lowest level of x_4 and the highest level of x_5 based on historical data. Furthermore, selecting optimal policy control variables also considers maintaining minimal industrial agglomeration and surpassing the high-level environmental regulatory intensity observed in the historical data.

Figure 10(b) provides a detailed explanation of the variation in the maximum cement shipment volume, $\max(\phi_2(x))$, at different levels of market control variables $x_4 \in [-0.3506, 2.1846]$ and $x_5 \in [-1.5405, 2.5205]$. It is evident that the increase in x_5 has a more significant effect on the maximum cement shipment volume compared to the changes in the x_4 direction. It is worth noting that neither the effect on $\max(\phi_2(x))$ of x_4 nor x_5 is monotonic. In Figure 10(b), we can observe the presence of a concave curve on the surface of $\max(\phi_2(x))$. This concave curve exerts a downward force, causing the two sides to form upwardly curved surfaces. When considering individuals with equal levels of cement export, it can be observed that the minimum value of the $\max(\phi_2(x))$ within the fluctuation range around x_5 occurs on the concave curve. Likewise, at the same level of x_5 , the $\max(\phi_2(x))$ value on the concave curve is also the lowest among the corresponding $\max(\phi_2(x))$ within the fluctuation range of x_4 .

Figure 11 Illustration of the optimal degree of agglomeration and the optimal intensity of environmental regulation within the range $x_4 \in [-1.3506, 2.1846]$ and $x_5 \in [-1.5405, 2.5205]$ (a) optimal degree of agglomeration (b) optimal intensity of ER (see online version for colours)



According to Figure 11(a), it is apparent that the x_2 in the optimal combination of policy control variables, is divided into two visible parts by the same concave curve. Recalling equation (10), it is not difficult to see that the mathematical expression of this concave curve is actually $0.4663x_4 + (0.1369x_4 + 0.2445)x_5 = 0$. This study defines the concave

curve as the ‘optimisation trap’. The reason for such naming is primarily due to the following factors: Firstly, when the market control variables align with the specific relationship we previously identified, the corresponding $\max(\phi_2(x))$ is lower than the results obtained from any combination of market control variables within the interval $x_4 \in [-1.3506, 2.1846)$ and $x_5 \in [-1.5405, 2.5205]$. Secondly, adhering to this relationship makes adjustments to our policy control variables ineffective, as any values assigned to these variables would not influence the optimisation process outlined in the previous analysis. On the left side of the ‘optimisation trap’, namely when $0.4663x_4 + (0.1369x_4 + 0.2445)x_5 < 0$, the industrial agglomeration is fixed at its lowest level, $x_2 = -2.1993$, yielding the optimal solution. The selection of optimal environmental regulation intensity lies within the range $[2.7038, 7.88]$, and as the export volume decreases, the environmental regulation intensity in the optimal decision becomes higher (as shown in Figure 11(b)). Moreover, at the same level of x_4 , regardless of the value of x_5 , there is no significant difference in the choice of optimal environmental regulation intensity. When $0.4663x_4 + (0.1369x_4 + 0.2445)x_5 > 0$, enhancing industrial agglomeration to its highest level at $x_2 = 1.3036$ would contribute to maximising cement shipment while controlling carbon dioxide emissions. Within the range of variation of x_5 , the optimal environmental regulation intensity also remains indifferent at the same level of x_4 . However, a notable distinction emerges between the cases on the left side of the ‘optimisation trap’ and those on the right. On the right side of the ‘optimisation trap’, we observe that the optimal environmental regulation intensity gradually and modestly increases with the rise in cement export volume.

5 Conclusions

In the context of escalating environmental concerns, the cement industry’s high pollution and energy intensity present distinct challenges for carbon emission reduction. This study scrutinises the efficacy of environmental regulation within the ‘inspection on government’ paradigm, with a focus on China, the epicentre of global cement production. We employ a comprehensive framework that integrates environmental science, statistical analysis, and economic objectives to evaluate the nexus between regulatory oversight and industry advancement. Our findings elucidate the critical role of carbon dioxide emissions per unit of cement output and cement shipment volume as benchmarks for environmental and economic performance. We reveal that heightened environmental regulation stringency substantially diminishes emissions, countering the notion that stringent regulations stifle industry growth. Specifically, a 10% increase in regulatory stringency corresponds to a 6.041% reduction in CO₂ emissions per unit of cement produced. Furthermore, the influence of market control variables – cement prices, export volumes, and FDI in construction – on emissions and shipment volumes is also significant. Notably, a lower level of industrial agglomeration, while enhancing energy efficiency, contributes to emission reductions only when export volumes exceed historical averages. This underscores the necessity for policy adjustments to be market-responsive.

Moreover, our analysis uncovers an ‘optimisation trap,’ wherein policy control variables become ineffective under specific market conditions, particularly when export volumes are low. This finding underscores the intricacy of harmonising environmental compliance with industrial development. To address this, we advocate for a strategic

approach that includes stringent environmental regulations, nuanced management of industrial agglomeration levels, and prudent FDI in the construction sector. This approach is pivotal for achieving a synergistic outcome where carbon reduction and cement shipment maximisation are concurrently realised, especially in scenarios with high export volumes. In recognition of the interconnected nature of environmental challenges, China's strategic environmental policies extend beyond direct emissions reduction to encompass waste management, reinforcing the broader air pollution control strategies. The nation has issued forward-looking guidelines that advocate for the establishment of a comprehensive waste recycling system, which is intended to cover all sectors and processes, aiming for an annual utilisation volume of bulk solid waste to reach 4 billion tons by the year 2025. This proactive stance on waste management not only mitigates the environmental stress associated with waste disposal but also supports air quality enhancement, synergistically aligning with the industry's emission reduction targets.

Consequently, the insights from this study can inform environmental regulatory decision-making in the cement industry and other sectors undergoing green transitions. Future research should delve into environmental regulatory efficiency and the balance between compliance and development, particularly within the 'enterprise supervision' framework. By building on our methodology, these investigations can provide more comprehensive guidance for optimising environmental policies and fostering sustainable industrial development. By enhancing our understanding of the 'inspection on government' framework, we can bolster the industry's green efficiency and economic performance, aligning with global ecological conservation objectives.

Acknowledgements

We gratefully acknowledge the assistance of Dongguan City University (Major Research and Cultivation Project 2020, 2020YZDYB06R) and the Department of Education of Guangdong Province (The Youth Innovation Talent Program of Guangdong for Colleges and Universities, 2019WQNCX153).

References

- Ahmed, K. (2020) 'Environmental policy stringency, related technological change and emissions inventory in 20 OECD countries', *Journal of environmental Management*, Vol. 274, Article no. 111209.
- Albulescu, C.T., Boatca-Barabas, M.E. and Diaconescu, A. (2022) 'The asymmetric effect of environmental policy stringency on CO2 emissions in OECD countries', *Environmental Science and Pollution Research*, Vol. 29, No. 18, pp.27311–27327.
- Assamoi, G.R. and Wang, S. (2023) 'Asymmetric effects of economic policy uncertainty and environmental policy stringency on environmental quality: evidence from China and the United States', *Environmental Science and Pollution Research*, Vol. 30, No. 11, pp.29996–30016.
- Atıcı, R., Aytaş, A. and Sağır, S. (2020) 'The effect of solar and geomagnetic parameters on total electron content over Ankara, Turkey', *Advances in Space Research*, Vol. 65, No. 9, pp.2158–2166.
- Bao, Q., Shao, M. and Yang, D. (2021) 'Environmental regulation, local legislation and pollution control in China', *Environment and Development Economics*, Vol. 26, No. 4, pp.321–339.

- Bildirici, M.E. (2019) 'Cement production, environmental pollution, and economic growth: evidence from China and USA', *Clean Technologies and Environmental Policy*, Vol. 21, No. 4, pp.783–793.
- Busico, G., Kazakis, N., Cuoco, E. et al. (2020) 'A novel hybrid method of specific vulnerability to anthropogenic pollution using multivariate statistical and regression analyses', *Water Research*, Vol. 171, Article no. 115386.
- Chaudhary, I., Mazumdar, K. and Vazirani, S. (2021) *New Opportunities for Steel in Construction and Infrastructure*, Crisil Research [online] <https://www.crisil.com/en/home/our-analysis/reports/2021/01/new-opportunities-for-steel-in-infrastructure-and-construction.html> (accessed 24 May 2023).
- Cozzi, L., Chen, O. et al. (2023) *CO₂ Emissions in 2022*, International Energy Agency, Paris [online] <https://www.iea.org/reports/co2-emissions-in-2022>, License: CC BY 4.0 (accessed 23 May 2023).
- De, M., Das, B. and Maiti, M. (2018) 'Green logistics under imperfect production system: a rough age based multi-objective genetic algorithm approach', *Computers and Industrial Engineering*, Vol. 119, pp.100–113.
- Dinda, S. (2004) 'Environmental Kuznets curve hypothesis: a survey', *Ecological Economics*, Vol. 49, No. 4, pp.431–455.
- Ding, M.R. (2021) 'Analysis of carbon emissions status and discussion on key pathways for emission reduction in the cement industry', *China Cement*, Vol. 7, pp.46–49.
- Duan, Y., Ji, T. and Yu, T. (2021) 'Reassessing pollution haven effect in global value chains', *Journal of Cleaner Production*, Vol. 284, Article no. 124705.
- Ellis, A.B. and Grinstead, P. (2008) 'Hidden lessons: how a focus on slope-like properties of quadratic functions encouraged unexpected generalizations', *The Journal of Mathematical Behavior*, Vol. 27, No. 4, pp.277–296.
- Fiorino, D.J. (2006) *The New Environmental Regulation*, Mit Press.
- Foreign Investment Administration (2023) *Report on Foreign Investment in China*, 2022, Ministry of Commerce, P.R. China [online] <http://images.mofcom.gov.cn/wzs/202301/20230104194942451.pdf> (accessed 23 June 2023).
- Fuqian, F. (2023) *The Supply-side Revolution with Chinese Characteristics*, Routledge, London.
- Garatti, A., Poulou, A. and Mourtada, L. (2021) *Joe Biden's Infrastructure Plan: Defying Gravity*, Allianz Research [online] https://www.allianz.com/content/dam/onemarketing/azcom/Allianz_com/economic-research/publications/specials/en/2021/april/2021_04_06_Bideninfrastructureplan.pdf (accessed 4 September 2023).
- Ghojogh, B., Crowley, M., Karray, F. et al. (2023) 'Principal component analysis', *Elements of Dimensionality Reduction and Manifold Learning*, pp.123–154, Springer International Publishing, Cham.
- Guo, Z., Bai, X., Liu, S. et al. (2022) 'Heterogeneous variations on historical and future trends of CO₂ and multiple air pollutants from the cement production process in china: emission inventory, spatial-temporal characteristics, and scenario projections', *Environmental Science and Technology*, Vol. 56, No. 20, pp.14306–14314.
- Han, J., Li, G., Shen, Z. et al. (2022) 'Manufacturing transfer and environmental efficiency: Evidence from the spatial agglomeration of manufacturing in China', *Journal of Environmental Management*, Vol. 314, Article no. 115039.
- Huang, D.Y. and Yang, D.L. (2016) 'The process and dilemma of assessment-style regulation in China: a case study of the target assessment on pollutant emission reduction', *Journal of Political Science*, Vol. 129, No. 4, pp.101–112.
- IEA (2018) *Technology Roadmap – Low-Carbon Transition in the Cement Industry*, IEA, Paris, License: CC BY 4.0.
- Jena, M.C., Mishra, S. and Moharana, H.S. (2020) 'Air pollution from cement plants: case study on particulate matter in Bihar, India', *Environmental Claims Journal*, Vol. 32, No. 3, pp.221–232.

- Jenkins, D.G. and Quintana-Ascencio, P.F. (2020) 'A solution to minimum sample size for regressions', *PLoS One*, Vol. 15, No. 2, p.e0229345.
- Katoch, S., Chauhan, S.S. and Kumar, V. (2021) 'A review on genetic algorithm: past, present, and future', *Multimedia Tools and Applications*, Vol. 80, No. 5, pp.8091–8126.
- Kim, H. (2022) 'A finite sample correction for the panel Durbin–Watson test', *Applied Economics*, Vol. 54, No. 28, pp.3197–3205.
- Lee, C.C., Feng, Y. and Peng, D. (2022) 'A green path towards sustainable development: the impact of low-carbon city pilot on energy transition', *Energy Economics*, Vol. 115, Article no. 106343.
- Leffel, B., Tavasoli, N., Liddle, B. et al. (2022) 'Metropolitan air pollution abatement and industrial growth: Global urban panel analysis of PM₁₀, PM_{2.5}, NO₂ and SO₂', *Environmental Sociology*, Vol. 8, No. 1, pp.94–107.
- Li, J. and Xu, Y. (2023) 'Does fiscal decentralization support green economy development? Evidence from China', *Environmental Science and Pollution Research*, Vol. 30, No. 14, pp.41460–41472.
- Luo, Y., Guo, C., Ali, A. et al. (2022) 'A dynamic analysis of the impact of FDI, on economic growth and carbon emission, evidence from China, India and Singapore', *Environmental Science and Pollution Research*, Vol. 29, No. 54, pp.82256–82270.
- Mallagray, J.V., Anagnostou, J., Stec, M., Li, T. and Schlorke, S. (2021) *Strengthening Sustainability in the Cement Industry*, International Finance Corporation [online] <https://www.ifc.org/content/dam/ifc/doc/mgrt/ifc-strengtheningsustainability-cement-web.pdf> (accessed 6 September 2023).
- Mandal, S.K. (2010) 'Do undesirable output and environmental regulation matter in energy efficiency analysis? Evidence from Indian cement industry', *Energy Policy*, Vol. 38, No. 10, pp.6076–6083.
- Métais, C. and Roger, T. (2022) 'Are retail investors less aggressive on small price stocks?', *Journal of Financial Markets*, Vol. 59, Article no. 100685.
- Ministry of Ecology and Environment (2020) *Measures for Ecological Environment Standards*, December 15th, 2020, P.R. China [online] https://www.mee.gov.cn/xxgk/2018/xxgk/xxgk02/202012/t20201218_813921.html, DOI: 000014672/2020-01835.
- Mishra, U.C., Sarsaiya, S. and Gupta, A. (2022) 'A systematic review on the impact of cement industries on the natural environment', *Environmental Science and Pollution Research*, Vol. 29, No. 13, pp.18440–18451.
- Nakamura, R. and Paul, C.J.M. (2019) 'Measuring agglomeration', *Handbook of Regional Growth and Development Theories*, pp.386–412, Edward Elgar Publishing, Cheltenham, UK.
- National Bureau of Statistics (2023) *China Industry Statistical Yearbook*, China Statistical Publishing House, Beijing, 2000–2022.
- National Minerals Information Center (2024) *Mineral Commodity Summaries-Cement*, US Geological Survey (USGS) Publications Warehouse, Reston, 1996–2024.
- Pascale, A. and Greig, C. (2021) *Princeton's Net-Zero America study Annex K: Cement Industry Transition*, Princeton University, Princeton, NJ, USA.
- Petroche, D.M. and Ramirez, A.D. (2022) 'The environmental profile of clinker, cement, and concrete: a life cycle perspective study based on ecuadorian data', *Buildings*, Vol. 12, No. 3, pp.311–328.
- Porter, M.E. and Van der Linde, C. (1995) 'Toward a new conception of the environment-competitiveness relationship', *Journal of Economic Perspectives*, Vol. 9, No. 4, pp.97–118.
- Ritchie, H., Roser, M. and Rosado, P. (2020) *CO₂ and Greenhouse Gas Emissions* [online] <https://ourworldindata.org/co2-and-greenhouse-gas-emissions> (accessed 1 November 2023).
- Shin, Y., Kim, Z., Yu, J. et al. (2019) 'Development of NO_x reduction system utilizing artificial neural network (ANN) and genetic algorithm (GA)', *Journal of Cleaner Production*, Vol. 232, pp.1418–1429.

- Singhania, M. and Saini, N. (2021) 'Demystifying pollution haven hypothesis: role of FDI', *Journal of Business Research*, Vol. 123, pp.516–528.
- Tanaka, K. and Managi, S. (2021) 'Industrial agglomeration effect for energy efficiency in Japanese production plants', *Energy Policy*, Vol. 156, Article no. 112442.
- Tkachenko, N., Tang, K., McCarten, M. et al. (2023) 'Global database of cement production assets and upstream suppliers', *Scientific Data*, Vol. 10, No. 1, p.696.
- United States Environmental Protection Agency (EPA) (2021) *U.S. Cement Industry Carbon Intensities*, 2019, EPA 430-F-21-004.
- Wan, J., Qin, C., Wang, Q. et al. (2022) 'A brief overview of the 13th five-year plan for the protection of ecological environment', in Wang, J., Wang, X. and Wan, J. (Eds.): *Environmental Strategy and Planning in China*, Springer, Singapore.
- Wang, H., Lu, X., Deng, Y. et al. (2019) 'China's CO₂ peak before 2030 implied from characteristics and growth of cities', *Nature Sustainability*, Vol. 2, No. 8, pp.748–754.
- Wang, Q., Xu, X. and Liang, K. (2021) 'The impact of environmental regulation on firm performance: evidence from the Chinese cement industry', *Journal of Environmental Management*, Vol. 299, Article no. 113596.
- Wang, S., Zhang, R., Wan, L. et al. (2023a) 'Has central government environmental protection interview improved air quality in China?', *Ecological Economics*, Vol. 206, Article no. 107750.
- Wang, X., Ge, Q., Geng, X. et al. (2023b) 'Unintended consequences of combating desertification in China', *Nature Communications*, Vol. 14, No. 1, p.1139.
- Xie, Q., Wang, X. and Cong, X. (2020) 'How does foreign direct investment affect CO₂ emissions in emerging countries? New findings from a nonlinear panel analysis', *Journal of Cleaner Production*, Vol. 249, Article no. 119422.
- Xie, R. and Teo, T.S.H. (2022) 'Green technology innovation, environmental externality, and the cleaner upgrading of industrial structure in China – considering the moderating effect of environmental regulation', *Technological Forecasting and Social Change*, Vol. 184, Article no. 122020.
- Xu, G., Xue, D. and Rehman, H. (2022) 'Dynamic scenario analysis of CO₂ emission in China's cement industry by 2100 under the context of cutting overcapacity', *Mitigation and Adaptation Strategies for Global Change*, Vol. 27, No. 8, pp.1–40.
- Yan, Z., Zhou, Z. and Du, K. (2023) 'How does environmental regulatory stringency affect energy consumption? Evidence from Chinese firms', *Energy Economics*, p.106503.
- Yang, D.L. and Xue, L. (2016) *Comparison of Environmental Governance System and Governance Capacity Between China and the United States*, Center for industrial development and Environmental governance (CIDEG) Report, Tsinghua University.
- Yi, X. and Liu, S. (2022) 'The optimal decision rule of environmental regulation: an analysis of the cement industry', *Journal of Cleaner Production*, Vol. 336, Article no. 130410.
- Young, O.R., Guttman, D., Qi, Y. et al. (2015) 'Institutionalized governance processes: comparing environmental problem solving in China and the United States', *Global Environmental Change*, Vol. 31, pp.163–173.
- Zhai, Y.M., Sun, W.Q., Tsai, S.B. et al. (2018) 'An empirical study on entrepreneurial orientation, absorptive capacity, and SMEs' innovation performance: a sustainable perspective', *Sustainability*, Vol. 10, No. 2, pp.1–14.
- Zhao, C. and Wang, B. (2021) 'Does China's low-carbon pilot policy promote foreign direct investment? An empirical study based on city-level panel data of China', *Sustainability*, Vol. 13, No. 19, p.10848.

Appendix

Table A1 Illustration of the explained and explanatory variables

<i>Variable</i>	<i>Notation</i>	<i>Annotation</i>	<i>Unit</i>
Observation variables	ζ	amount of carbon dioxide emissions per unit of cement output CO_2/Q	ton
	η	annual cement shipment volumes	ton
Policy control variables	x_1	environmental regulatory stringency	N/A
	x_2	industry agglomeration level	N/A
Market control variables	x_3	average mill price of cement	dollar
	x_4	export volume	ton
	x_5	FDI in the construction industry	dollar

Table A2 Definitions of nomenclature

<i>Term</i>	<i>Definition</i>
2DS	2°C scenario
FBGR	Fixed base growth rate
FDI	Foreign direct investment
GAs	Genetic algorithms
GLM	Generalised linear model
MEE	Ministry of ecology and environment, china
PCA	Principal component analysis
PHH	Pollution haven hypothesis
P.H.	Porter hypothesis
SBX	Simulated binary crossover (a genetic algorithm operator)
SMLR	Stepwise multiple linear regression
VIF	Variance inflation factor

Table A3 Properties of national emission standards of air pollutants for cement industry

<i>Year</i>	<i>Sources</i>	<i>Pollutants</i>	<i>FBGR of the number of improved emission limits for pollutants</i>	<i>FBGR of the maximum improvement rate of emission limits</i>	<i>Published time/status</i>
1989–1995	Rotary kiln, shaft kiln, dryer, drying mill, coal mill, cooler, crusher, mill, packing machine, ventilation equipment	dust, CO	0	0	1985/ formulation
1996–2003	Rotary kiln, shaft kiln, dryer, drying mill, coal mill, cooler, crusher, mill, packing machine, ventilation equipment	dust, SO ₂ , NO _x , fluoride	3	1.7143	1996/first revision

Table A3 Properties of national emission standards of air pollutants for cement industry (continued)

<i>Year</i>	<i>Sources</i>	<i>Pollutants</i>	<i>FBGR of the number of improved emission limits for pollutants</i>	<i>FBGR of the maximum improvement rate of emission limits</i>	<i>Published time/status</i>
2004–2013	Cement kiln(rotary), cement kiln(shaft), inline kiln, raw material dryer, drying and grinding mill, coal grinding mill, clinker cooler, crusher, raw mill system, packing machine, ventilation equipment	Particulate matter (pm), SO_2 , NO_x , fluoride	4	1.7143	2004/second revision
2014–2020	cement kiln(rotary), cement kiln(shaft), inline kiln, waste heat utilisation system of kiln exhaust gas, raw material dryer, drying and grinding mill, coal grinding mill, clinker cooler, crusher, raw mill system, packing machine, ventilation equipment	Particulate matter (pm), SO_2 , NO_x , fluoride, Hg, NH_3	6	2.5715	2014/third revision

Table A4 Illustration of the carbon dioxide emission corresponding to max (x_1) under the explanatory variables

x_2	x_4	x_3				
		-1.1162	-0.1253	0.96	1.460	1.9555
-2.1993	-1.3506	1.4401	0.4111	-0.0066	0.0509	0.2629
	-0.6553	0.6657	-0.3633	-0.781	-0.7235	-0.5115
	0.04	-0.1088	-1.1377	-1.5554	-1.4979	-1.2859
	1.5697	-1.8125	-2.8414	-3.2591	-3.2016	-2.9896
	2.9603	-3.3613	-4.3902	-4.8079	-4.7504	-4.5384
-0.0524	-1.3506	0.3739	-0.6551	-1.0728	-1.0153	-0.8033
	-0.6553	0.1484	-0.8806	-1.2983	-1.2408	-1.0288
	0.04	-0.0771	-1.1061	-1.5238	-1.4663	-1.2543
	1.5697	-0.5732	-1.6022	-2.0199	-1.9624	-1.7504
	2.9603	-1.0242	-2.0532	-2.4709	-2.4134	-2.2014
1.3036	-1.3506	-0.2995	-1.3285	-1.7461	-1.6887	-1.4767
	-0.6553	-0.1783	-1.2073	-1.625	-1.5675	-1.3555
	0.04	-0.0572	-1.0861	-1.5038	-1.4463	-1.2343
	1.5697	0.2094	-0.8195	-1.2372	-1.1798	-0.9677
	2.9603	0.4518	-0.5772	-0.9949	-0.9374	-0.7254

Note: *All data in the table are standardised.

Table A5 Illustration of the cement shipment corresponding to $\max(x_1)$ under the explanatory variables

x_2	x_5	x_3				
		-1.1162	-0.1253	0.96	1.460	1.9555
-2.1993	-1.5405	-1.1774	-0.2987	0.0814	0.051	-0.1063
	-0.7545	-1.6144	-0.7357	-0.3556	-0.386	-0.5433
	0.0315	-1.8752	-0.9965	-0.6165	-0.6468	-0.8041
	1.3415	-1.9186	-1.0399	-0.6599	-0.6902	-0.8475
	2.5205	-1.5394	-0.6607	-0.2807	-0.311	-0.4683
-0.0524	-1.5405	-0.4459	0.4328	0.8128	0.7825	0.6251
	-0.7545	-0.5749	0.3038	0.6838	0.6535	0.4962
	0.0315	-0.5278	0.3509	0.731	0.7006	0.5433
	1.3415	-0.0579	0.8208	1.2009	1.1705	1.0132
	2.5205	0.7833	1.662	2.0421	2.0117	1.8544
1.3036	-1.5405	0.016	0.8947	1.2748	1.2444	1.0871
	-0.7545	0.0816	0.9603	1.3403	1.31	1.1527
	0.0315	0.3232	1.2019	1.582	1.5516	1.3943
	1.3415	1.1173	1.996	2.3761	2.3457	2.1884
	2.5205	2.2503	3.129	3.5091	3.4787	3.3214

Note: *All data in the table are standardised.