FORMATION OF STRATEGIES BASED ON RESOURCE-SAVING AND ECOLOGICAL INNOVATIONS IN LARGE CONSTRUCTION ENTERPRISES IN A GREEN ECONOMY CONTEXT

Raximov Qodir Ergashevich
Associate Professor, PhD Tashkent University of Architecture and Construction
G‘ulomova Shaxlo Baxtiyor qizi
PhD student of Tashkent University of Architecture and Construction
Rejaboyev Nodir Sherzod o‘g‘li
Master student of Tashkent University of Architecture and Construction

Annotation: This study investigates the formation of resource-saving and eco-innovative strategies within large construction enterprises in the context of the global transition to a green economy. Recognizing the construction sector as a major energy consumer and carbon emitter, this research addresses the limitations of traditional efficiency metrics by employing a comprehensive three-stage Slacks-Based Measure Data Envelopment Analysis (SBM-DEA) combined with Stochastic Frontier Analysis (SFA) and a Tobit panel regression model. The SFA effectively isolates the impacts of external environmental variables—such as regional economic development and marketization—and random statistical noise to accurately assess true managerial and technological efficiency. Results reveal that the baseline eco-efficiency of the industry is suboptimal when external favorable conditions are removed, and a significant portion of enterprises suffer from scale inefficiency. Furthermore, the Tobit regression identifies that the scale of auxiliary industries (such as design and consulting), a shift toward renewable energy structures, and state capital are critical positive determinants of true eco-efficiency. The findings provide empirical evidence that while strict environmental regulations may initially impose productivity costs, strategic alignment with eco-innovation, supply chain digitalization, and the establishment of a Green Corporate Image (GCI) ultimately foster long-term competitive advantage and sustainable development in the construction sector.

Keywords: Green economy; Eco-innovation; Resource efficiency; Construction industry; SBM-DEA; Stochastic Frontier Analysis (SFA); Tobit regression; Sustainable development; ESG transparency

ФОРМИРОВАНИЕ СТРАТЕГИЙ НА ОСНОВЕ РЕСУРСОСБЕРЕГАЮЩИХ И ЭКОЛОГИЧЕСКИХ ИННОВАЦИЙ НА КРУПНЫХ СТРОИТЕЛЬНЫХ ПРЕДПРИЯТИЯХ В УСЛОВИЯХ ЗЕЛЁНОЙ ЭКОНОМИКИ

Рахимов Қодир Эргашевич
доцент, PhD, Ташкентский архитектурно-строительный университет
Гуломова Шахло Бахтиёр кизи
PhD student Ташкентского архитектурно-строительного университета
Режабоев Нодир Шерзод угли
магистрант Ташкентского архитектурно-строительного университета

Аннотация:
Данное исследование посвящено формированию ресурсосберегающих и эко-инновационных стратегий на крупных строительных предприятиях в условиях глобального перехода к зелёной экономике. Учитывая, что строительный сектор является одним из крупнейших потребителей энергии и источников выбросов углерода, в работе рассматриваются ограничения традиционных методов оценки эффективности. Для этого применяется комплексный трёхэтапный метод анализа SBM-DEA (Slacks-Based Measure Data Envelopment Analysis) в сочетании со стохастическим граничным анализом (SFA) и панельной регрессией Тобита.

Метод SFA позволяет эффективно изолировать влияние внешних факторов окружающей среды — таких как уровень регионального

экономического развития и рыночная либерализация, — а также случайного статистического шума для более точной оценки реальной управленческой и технологической эффективности. Результаты исследования показывают, что базовая эко-эффективность отрасли остаётся на недостаточном уровне после исключения благоприятных внешних условий, а значительная часть предприятий сталкивается с проблемой неэффективности масштаба.

Кроме того, регрессия Тобита выявила, что масштаб вспомогательных отраслей (таких как проектирование и консалтинг), переход к структурам возобновляемой энергетики и государственный капитал являются ключевыми положительными факторами истинной эко-эффективности. Полученные результаты предоставляют эмпирические доказательства того, что, несмотря на первоначальные издержки, связанные со строгими экологическими требованиями, стратегическая ориентация на эко-инновации, цифровизацию цепочек поставок и формирование Green Corporate Image (GCI) в долгосрочной перспективе способствует повышению конкурентоспособности и устойчивому развитию строительного сектора.

Ключевые слова:
зелёная экономика; эко-инновации; ресурсная эффективность; строительная отрасль; SBM-DEA; стохастический граничный анализ (SFA); регрессия Тобита; устойчивое развитие; ESG-прозрачность.

Introduction: The global transition to a green economy fundamentally transforms the paradigms of industrial development, requiring the corporate sector to integrate environmental sustainability principles into the core of their long-term strategies. In the context of these transformations, the construction industry occupies a special place due to its colossal environmental impact and unprecedented resource intensity. International studies indicate that the construction sector is the largest consumer of energy and a major source of carbon emissions, consuming over 50% of all global energy resources [1]. These resources are expended across various phases of the building lifecycle, including the production of construction materials, equipment operation, direct construction and installation works, and subsequent waste disposal [2]. The traditional extensive model of construction enterprise development, characterized by high levels of investment, excessive raw material consumption, and significant volumes of harmful emissions, demonstrates its complete untenability in the face of the climate crisis and the depletion of natural resources [3]. The creation of high-quality (desirable) products of economic activity is always accompanied by the production of undesirable (by-product) outcomes, such as greenhouse gas (GHG) emissions, which cause ocean acidification, heat waves, droughts, and reduced availability of clean drinking water, as well as provoke an increase in respiratory diseases among the population[4].

In response to these global challenges, and under the pressure of international agreements such as the Kyoto Protocol and the Paris Agreement, which oblige countries to reduce GHG emissions, large construction enterprises are forced to reconsider their production processes [5]. The formation of strategies based on resource-saving and ecological innovations (eco-innovations) becomes not just a matter of social responsibility, but a key factor for survival and ensuring competitiveness in the international market [6]. Eco-innovations and resource-saving technologies are considered crucial tools for mitigating ecological risks and building a sustainable, competitive economy of the future [7]. However, the process of integrating such strategies is complicated by the multifaceted nature of the concept of environmental efficiency (eco-efficiency) and the difficulties in its objective quantitative assessment under the influence of multiple external factors outside the managerial control of enterprises [8].

The problem is that traditional approaches to measuring the production efficiency of construction companies focus solely on the ratio of financial costs to economic returns, completely ignoring environmental externalities (spillover effects), such as the generation of construction waste and carbon dioxide emissions

[9]. Moreover, even when using basic Data Envelopment Analysis (DEA) models, the results are often distorted due to managerial inefficiency, the influence of the external macroeconomic environment, and statistical errors [10]. Without an accurate understanding of their true eco-efficiency, enterprises cannot identify bottlenecks in resource allocation and develop adequate strategies for green modernization.

The scientific novelty and practical significance of the study lie in the fact that it not only provides efficiency metrics cleared of statistical noise but also synthesizes these quantitative data with the qualitative aspects of ESG (Environmental, Social, and Governance) integration, public opinion pressure, and the use of global open databases [11]. The results of the study form a scientifically grounded foundation for the development of targeted decarbonization roadmaps in the construction sector, which is of particular value to policymakers, investors, and industry leaders in both developed and developing economies around the world [12].

2. Literature Review

In modern economic theory, eco-efficiency is understood as the ability of economic entities to generate maximum value added (or the output of desired products) while simultaneously minimizing the consumption of natural resources and reducing negative environmental impacts, such as greenhouse gas emissions and waste generation [13]. The Organization for Economic Co-operation and Development (OECD) emphasizes that eco-innovations create a positive environmental effect precisely through resource saving, which makes them the cornerstone of any corporate resource-saving strategy [14]. Studies show that eco-innovations positively affect both general and specific resource use, and also promote the development of secondary material recycling processes [15].

In the context of the construction industry, eco-innovations take various forms: from the use of new nanotechnology-based composite materials, such as carbon columns replacing heavy resource-intensive concrete, to the implementation of building automation systems and smart grid technologies that optimize energy consumption at the level of individual districts and entire cities [16]. The dematerialization of the industry is achieved by shifting the focus to creating lighter structures that function as independent ecological systems. It is important to note that technological improvements in the field of eco-efficiency are dynamic. For example, macroeconomic studies of Asian and African economies using the Translog log-linear production function have proven that replacing fossil fuels with renewable energy sources and increasing the share of a skilled workforce are critical for improving technical eco-efficiency over time [17]. At the same time, an inverted U-shaped relationship was found between the share of fossil fuel consumption and eco-efficiency, indicating the existence of a critical threshold beyond which traditional energy sources begin to catastrophically destroy the economic returns of environmental investments [17].

In this mechanism, the formation of a Green Corporate Image (GCI) plays a crucial mediating role. Enterprises respond to public pressure not only because of the threat of sanctions but also to strengthen their image, which increases the trust of investors and clients. Market competition acts as a moderator in this scheme: under fierce competition, the impact of EPOP on GCI can be modified, forcing companies to integrate green dynamic capabilities faster [18]. The Vietnamese experience also confirms that in response to the evolving environmental landscape and the growing demand for green buildings, construction enterprises are compelled to implement green dynamic capabilities to reduce their environmental impact, strengthen public trust, and, as a result, increase profit margins and chances of securing contracts from public and private entities [19].

In addition to financial terminals, specialized open industry platforms play a massive role. The Embodied Carbon in Construction Calculator (EC3) became the first free open-source database containing thousands of digital Environmental Product Declarations (EPDs). This tool allows designers and construction companies to directly measure, compare, and reduce carbon emissions in the materials supply chain at the level of specific projects. At the national level in the US, the Building Performance Database (BPD) operates as the largest dataset of anonymized information regarding the energy characteristics of commercial and residential properties, aggregating data from government, utilities, and private companies. In turn, the ENERGY STAR certification program and the EEBA & ecomedes database of green building materials provide consumers and contractors with reliable benchmarks when selecting resource-saving technologies. Similarly, the World Bank's Global Indicators Group runs the "Building Green" project, which aggregates data on building energy codes and standards, as well as enforcement mechanisms worldwide. The toolkit of the UNEP Finance Initiative (UNEP FI), particularly the Sustainability Risk Tool Dashboard, provides financial institutions with open access to over 100 tools for navigating climate, nature, and social risks.

Development of Assessment Methodology: DEA, SFA, and Tobit

The literature widely discusses methods for measuring production efficiency. The traditional DEA (Data Envelopment Analysis) method is a linear programming-based approach for evaluating the performance of comparable Decision-Making Units (DMUs). However, traditional models (such as the radial CCR or BCC models) are criticized because they measure efficiency solely through the ratio of inputs to outputs, without accounting for slack variables and ignoring external environmental factors, which inevitably leads to systematic bias in the estimates.

Since the efficiency values calculated using DEA are restricted to a range from 0 to 1, applying the traditional Ordinary Least Squares (OLS) method to identify factors affecting this efficiency leads to statistically incorrect and biased results. To solve the problem of truncated data, economists universally use the Tobit regression model, which allows for a reliable estimation of the impact of institutional, economic, and structural factors on eco-efficiency. This integrated approach (SBM-DEA + SFA + Tobit) has become the gold standard in analyzing the energy efficiency and sustainable development of the construction sector worldwide.

3. Materials and Methods

This study relies on a complex multi-stage econometric procedure designed to accurately measure the eco-efficiency of large construction enterprises and identify its key determinants. The methodological framework consists of four sequential steps: constructing the initial non-radial SBM-DEA model, isolating environmental factors through SFA, recalculating the adjusted efficiency, and finally, Tobit panel regression analysis.

3.1. Stage 1: SBM-DEA Model Considering Undesirable Outputs

Unlike traditional DEA models, which assume a proportional change in all inputs or outputs (radiality) and can overestimate efficiency by ignoring slack variables, this study applies the Slacks-Based Measure (SBM) model. This model is optimized for handling undesirable environmental outputs, as resource saving implies a reduction in emissions without a mandatory proportional reduction in economic revenue.

Assume that the sample consists of *n* Decision-Making Units (DMUs) representing large construction enterprises. Each enterprise *j (j = 1, 2,..., n)* consumes *m* types of resource inputs $x \in R^m$ to produce s_1 types of desirable outputs $y^g \in R^{s_1}$ (revenues, completed projects) and s_2 types of undesirable outputs $y^b \in R^{s_2}$(CO_2 emissions, volume of construction waste). volume of construction waste). The input and output matrices are defined as

$$X=[x_1,\ldots,x_n]\in R^{m\times n} Y^g=[y_1^g,\ldots,y_n^g]\in R^{s_1\times n}$$

and $Y^b=[y_1^b,\ldots,y_n^b]\in R^{s_2\times n}$ Provided that $X>0, Y^g>0, Y^b>0$

the Production Possibility Set (PPS) is defined by the formula

$PPS=\{(x,y^g,y^b)\mid x\geq X\lambda, y^g\leq Y^g\lambda, y^b\geq Y^b\lambda, \lambda\geq 0\}$ The objective function of the SBM model for evaluating the efficiency of a specific enterprise $DMU_0(x_0,y_0^g,y_0^b)$ is calculated by solving the following non-linear programming problem

$$\rho^{¿} = min\, 1 - \frac{1}{m} \frac{\sum_{i=1}^{m} \frac{s_i^{-¿}}{x_{i0}}}{1 + \frac{1}{s_1 + s_2}\left(\sum_{r=1}^{s_1} \frac{s_r^g}{y_{r0}^g} + \sum_{t=1}^{s_2} \frac{s_t^b}{y_{t0}^b}\right)} ¿$$

Subject to the following constraints:

$x_0 = X\lambda + s^{-¿¿}\, y_0^g = Y^g \lambda - s^g\, y_0^b = Y^b \lambda + s^b\, y_0^b = Y^b \lambda + s^b$Where:

- $\rho^{¿}$ is the eco-efficiency value of the DMU, taking values from 0 to 1. If$\rho^{¿} \geq 1$ and all slack variables are equal to zero

¿

the enterprise is in an optimal state of resource allocation and lies on the efficient frontier

- γ is the intensity weight vector.
- $s^{-¿, s^g, s^b ¿}$ are the vectors of slack variables for inputs, desirable outputs, and undesirable outputs, respectively, representing the volumes of excess resource consumption and insufficient production of useful output.

The efficiency values calculated at this stage reflect the cumulative effect of managerial decisions, but they are distorted by the influence of the external macroeconomic environment and statistical noise, which requires a second stage of analysis.

3.2. Stage 2: Stochastic Frontier Analysis (SFA)

To isolate the influence of the external environment and random errors, the SFA model is applied. The dependent variable consists of the input slacks $S_{¿}$ obtained in the first stage for each *i*-th enterprise and *n*-th input. The independent variables are external environmental factors $Z_i$that affect efficiency but are not subjectively controlled by the construction industry's management.

The SFA regression equation takes the form :

$S_{ni} = f(Z_i, \beta_n) + v_{ni} + \mu_{ni} (n = 1,2,\dots,m; i = 1,2,\dots,K)$Where:

- S_{ni} is the slack of the n-th input for the i-th DMU.
- Z_i is a vector of external environmental variables (e.g., per capita GDP, degree of market openness).
- β_n is a vector of coefficients for environmental variables to be estimated.
- $f(Z_i, \beta_n)$ is the impact of the external environment on the input slack (usually expressed by the linear function $Z_i \beta_n$).
- $v_{ni} + \mu_{ni}$ is the mixed error term.
- $v_{ni} \sim N(0, \sigma_{vn}^2)$ represents random statistical noise (random error), reflecting the impact of force majeure or measurement inaccuracies.
- $\mu_{ni} \sim N^{+}(\mu, \sigma_{\mu n}^2)$ represents managerial inefficiency, which follows a truncated normal distribution and is non-negative. v_{ni} and μ_{ni} are assumed to be independent of each other.

The key metric in SFA is the parameter γ (gamma), defined as$\gamma = \sigma_{\mu n}^2 / (\sigma_{\mu n}^2 + \sigma_{vn}^2)$. If the value of γ is close to 1, this means that the predominant cause of slack variation is managerial inefficiency, and the application of SFA is justified. If γ is close to 0, random noise dominates

Using the SFA estimates, the input variables are adjusted to neutralize the advantages or disadvantages caused by the external environment. All enterprises are artificially placed into a "homogeneous" environment, that is, the most unfavorable one existing in the sample. The formula for adjusting inputs is :

$X_{ni}^{A} = X_{ni} + \left[\max_i (Z_i \hat{\beta}_n) - Z_i \hat{\beta}_n\right] + \left[\max_i (\hat{v}_{ni}) - \hat{v}_{ni}\right]$The first square bracket eliminates differences in the environmental (external) setting, and the second smooths out the impact of random factors. Thus, the adjusted input X_{ni}^{A} reflects the need for resources if all companies operated under the exact same and worst macroeconomic conditions.

3.3. Stage 3: Recalculation of Eco-efficiency

In the third stage, the adjusted input values $X_{¿}^{¿}$obtained through SFA and the initial output values $Y^{g}, Y^{b}$are re-entered into the SBM-DEA model (the equation from Stage 1). The efficiency indicators calculated at this stage reflect the true production and technological performance of construction corporations, completely cleared of the distorting influence of external factors and statistical noise, thereby providing an objective and scientific basis for strategic planning.

3.4. Stage 4: Tobit Panel Regression

Because the eco-efficiency values derived from the DEA model are truncated and strictly bounded between 0 and 1 (with a significant number of efficient enterprises having an exact score of 1), applying Ordinary Least Squares (OLS) to identify the determinants of efficiency would lead to biased and inconsistent estimates. Therefore, the censored Tobit regression model, developed by James Tobin in 1958, is universally applied in sustainable development methodology.

To analyze the impact of internal institutional, economic, and structural factors on eco-efficiency, the following panel model is specified :

$y_{¿}^{¿}=\beta_0+\sum_{k} \beta_k X_{kit}+u_{¿}, u_{¿} \sim N\left(0,\sigma^2\right)$Where $y_{¿}^{¿}$is a latent variable representing the enterprise's true propensity for eco-efficiency. The observed efficiency $y_{¿}$(the result of the 3rd stage DEA) is defined as :

$y_{¿}=\begin{cases} y_{¿}^{¿} & \text{if } y_{¿}^{¿}>0 \\ 0 & \text{if } y_{¿}^{¿}\leq 0 \end{cases}$ X_{kit} is a set of independent determinant variables defining the construction enterprise's capacity for resource saving, and β_k is the vector of corresponding coefficients. In this model, prior to regression, the data are tested for stationarity, cointegration, and multicollinearity (via Pearson correlation analysis), which guarantees the robustness of the econometric conclusions.

3.5. Selection of Variables and Data Sources

The formation of the indicator system is based on international standards for assessing the environmental footprint and operational intensity in the construction industry.

- *Input Variables:* Capital investment (volume of fixed asset investments, reflecting financial commitments and the level of technological modernization); Labor force (number of employed personnel, considering the labor-intensive nature of construction operations); Consumption of building materials (directly linked to resource depletion and embodied carbon); Energy consumption (linked to environmental burden); and the Level of technical equipment (mechanization).
- *Desirable Outputs:* Economic return (total value of completed construction projects, gross income of the construction industry).
- *Undesirable Outputs***:** Volume of carbon dioxide (CO_2) emissions and generation of solid construction waste.
- *Environmental Variables for SFA:* Degree of marketization (reflects the development level of market mechanisms in the region), Per capita GDP (economic development), and Intensity of environmental regulation (strictness of environmental legislation).
- *Determinants for the Tobit Model:* Development of auxiliary industries (scale of design, consulting, and supervision services — AIDD), Energy consumption structure (share of clean energy/electricity — ECS), Industrial development level (IDL), Degree of market openness (OD), Technological level (TL), and Share of state capital.

Data for modeling are extracted from official national statistical yearbooks (e.g., yearbooks of construction statistics for China and national statistics institutes of developing countries) and are verified through environmental and financial databases (Refinitiv Eikon, Bloomberg ESG, Trucost Environmental) to ensure international comparability.

4. Empirical Analysis Results

The analysis of construction enterprise eco-efficiency using the integrated approach demonstrates the complex dynamics of relationships among corporate governance, external environmental pressure, and structural market factors. The empirical calculation results, summarized based on data covering major construction markets (including Asian countries and large provinces of China), are presented according to the stages of the applied methodology.

4.1. Stage 1 Results: Initial Eco-efficiency (SBM-DEA)

At the initial stage, before accounting for the impact of external factors and stochastic noise, the eco-efficiency of construction corporations (Technical Efficiency — TE) was decomposed into Pure Technical Efficiency (PTE) and Scale Efficiency (SE). Empirical evidence indicates that the baseline resource-saving efficiency of the industry is at a suboptimal level.

An analysis of a representative sample of public construction companies (e.g., for the periods of 2019-2020) shows that the average green financing efficiency and eco-efficiency fluctuate in a narrow range of 0.772–0.776, indicating a lack of pronounced environmental advantages for companies in a traditional setting. In another study of emerging markets (a sample of 120 construction firms), the average technical efficiency was 84.4%, with pure technical efficiency reaching 93.2% and scale efficiency at 90.4%.

The most critical observation of the first stage is that the vast majority of large enterprises are constrained precisely by scale inefficiency. Only about 34.15%–36.59% of enterprises achieve strong DEA efficiency (a value equal to 1). Furthermore, over 60.98%–63.41% of companies are in the stage of "increasing returns to scale". This empirically proves that for more than half of the corporations in the industry, a simple and necessary step toward improving environmental productivity is the structural expansion and consolidation of their production capacities, which will lower the unit cost per environmental investment.

4.2. Stage 2 Results: Analysis of Environmental Factors (SFA)

To understand how regional and macroeconomic specifics distort the efficiency estimates of the 1st stage, an SFA model was constructed, where input slacks (inefficient use of labor, capital, materials, and energy) acted as dependent variables. Table 1 presents the regression coefficients of the impact of external variables on these slacks.

In the context of SFA, the interpretation of the coefficient signs is counterintuitive at first glance: a negative sign (-) means that the growth of a given external variable leads to a *reduction* in input slacks (waste), thereby *increasing* the eco-efficiency of enterprises. A positive sign (+) indicates that the factor provokes an increase in production waste and losses, *decreasing* efficiency. Log-likelihood values and high γ (gamma) parameters close to 1.00 (e.g., 0.99 or 1.00) at a 1% significance level convincingly confirm that deviations from the efficient frontier are predominantly caused by managerial inefficiency rather than random statistical sample noise, fully justifying the use of SFA

Table 1*: Results of SFA regression of the impact of environmental factors on construction enterprise input slacks.*

Environmental Variables	Impact on Input Slacks (Coefficientβ)	Statistical Significance Level	Final Impact on Eco-efficiency
Degree of marketization	Negative (-)	1%	Increases
Per capita GDP	Negative (-)	1%	Increases
Environmental regulation intensity	Negative (-)	1%	Decreases (in the short term)

The empirical data in Table 1 show the following:

- *Degree of marketization and Per capita GDP:* Both factors have significant negative coefficients. This proves that in regions with high per capita income and developed market institutions, the construction industry operates more cohesively. High marketization forces companies to control costs more strictly, minimizing investment redundancy and raw material consumption for a fixed output volume. Thus, regional economic wealth indirectly stimulates resource-saving strategies of enterprises.
- *Environmental regulation intensity:* Paradoxically, the correlation coefficients for all input slacks turned out to be positive and statistically significant. This means that strict environmental legislation and fines compel enterprises to hurriedly spend massive resources on compliance with new standards (installing filters, purchasing new, untested technologies), which, with an unchanged volume of construction output, increases the inefficiency of capital and equipment use in the short term, leading to a drop in production performance.

4.3. Stage 3 Results: Adjusted True Eco-efficiency

After adjusting the inputs considering the worst manifestations of the external environment and random noise (homogenization of the environment), the SBM-DEA model was recalculated. The results demonstrated substantial differences from the first stage.

As shown by a large-scale study of 55 public Chinese construction corporations (2017-2022), after clearing out external factors such as economic development and the total volume of completed projects, the average carbon emission efficiency was approximately 0.73. This means that a significant portion of the success attributed to management in the first stage was actually due to "hothouse" macroeconomic conditions. In a homogeneous environment, the pure technical efficiency of enterprises typically shows a decrease, but scale efficiency increases. Municipal installation enterprises demonstrate the highest average eco-efficiency (0.81), followed by decoration and renovation enterprises (0.78), while ecological landscaping companies, ironically, possess the greatest untapped potential for emissions reduction. Market leaders (such as the China State Construction Engineering Corporation) maintain their positions, but several other large corporations fail to reach even the 60% efficiency level.

4.4. Tobit Regression Results: Determinants of Strategy Formation

To assist enterprises in forming sound strategies, it is necessary to identify the internal industry mechanisms affecting the adjusted eco-efficiency indicators (in the range of 0 to 1). The application of Tobit panel regression made it possible to identify key drivers. Table 2 summarizes the coefficient results for the latent variable of eco-efficiency ECO¿

Table 2: Assessing the impact of internal determinants on the true eco-efficiency of construction corporations (Tobit model).

Independent Variables (Influencing Factors)	Tobit Coefficient (β)	P-value	Nature of Impact
Development of auxiliary industries (AIDD)	0.846	$p<0.01$	Strong positive
Energy consumption structure (ECS)	0.486	$p<0.01$	Positive
Level of industrial development (IDL)	0.186	$p<0.01$	Positive
Technological level (TL)	−0.053	$p<0.01$	Weak negative
Share of state capital	Significantly positive	$p<0.01$	Positive

The data indicate that the most powerful catalyst for eco-efficiency ($ +0.846$) is the scale of development of auxiliary industries (architectural design, consulting, engineering, and environmental supervision services). These very segments introduce the intellectual capital needed to create energy-efficient building plans. The energy consumption structure (a shift to renewable sources and a high share of process electrification) also has an extremely beneficial impact ($ +0.486$) on reducing the ecological footprint. At the same time, the technological level, measured by traditional indicators of mechanization, demonstrates a weak negative effect (-0.053). This suggests that mindlessly expanding a fleet of heavy construction equipment running on diesel fuel leads to increased emissions and negates any resource-saving initiatives, confirming conclusions about the limitations of traditional mechanization in the green paradigm. Furthermore, a high share of state capital and stable access to long-term credit (access to loans) correlate with higher eco-efficiency, which is particularly characteristic of developing countries where green investments require a strong financial safety net

5. Discussion

The results of the econometric analysis (DEA, SFA, Tobit) combined with research in environmental management and open ESG data allow for a comprehensive understanding of how large construction enterprises can adapt their business models. The discussion of the results obtained is structured around several strategic imperatives shaping the new ecosystem of green construction.

Interpreting the Contradictions of Environmental Regulation: Porter Hypothesis

The empirical fact of the negative short-term impact of environmental regulation intensity on eco-efficiency, revealed in the SFA analysis , requires deep managerial reflection. This result aligns with the classical economic theory of compliance costs; however, from a strategic perspective, it can be overcome through the mechanism known as the "Porter Hypothesis". Strict environmental frameworks initially reduce business margins, forcing the diversion of capital to pay eco-taxes or purchase filtration systems. But as the experience of international corporations shows, this external stress over time triggers processes of genuine, breakthrough eco-innovations. Enterprises seeking to offset these losses are forced to rebuild the entire technological chain, moving, for example, from resource-intensive monolithic technologies to prefabricated construction and the use of nanomaterials, which ultimately increases overall industry productivity. Nevertheless, as a study in Sweden shows, even with rising eco-efficiency, the absolute or relative decoupling of emissions and production volumes is not always achieved automatically, requiring continuous carbon footprint monitoring.

ESG Integration and Capitalization of Green Corporate Image (GCI)

One of the most important conclusions of the literature is the recognition that a resource-saving strategy cannot be isolated purely within a company's operational cycle; it must be broadcasted to the external environment. Environmental Public Opinion Pressure (EPOP) acts as a powerful incentive, compelling companies to change their behavioral paradigm. Given market transparency provided by platforms such as Bloomberg, Refinitiv Eikon, and Trucost Environmental, any attempt at "greenwashing" is immediately detected by algorithms analyzing over 600 sustainability parameters based on public corporate reports.

Construction enterprises are obliged to form a Green Corporate Image (GCI), which acts as a buffer between external pressure and financial performance. In a highly competitive environment (Market Competition), a green image becomes a key factor in securing institutional investments and winning public and private tenders. To achieve this, corporations must shift from passive legal compliance to proactive use of sustainable finance tools: issuing green bonds, integrating CSRD metrics into their annual reports, and regularly providing data on direct (Scope 1) and indirect (Scope 3) carbon dioxide emissions using carbon footprint standards.

Supply Chain Digitalization and the Role of Auxiliary Industries

The Tobit model results, which identified the colossal impact of auxiliary industries (coefficient +0.846) on eco-efficiency , radically shift the focus of strategic planning. It is critical for large construction corporations to realize that the battle for energy efficiency is won not on the construction site, but at the stage of architectural design and material selection.

This is where the potential of open international databases such as EC3 (Embodied Carbon in Construction Calculator) and BPD (Building Performance Database) is unlocked. EC3 grants access to thousands of digital Environmental Product Declarations (EPDs), allowing contractors and architects to audit the supply chain in real-time, selecting cement, steel, or insulation materials with the lowest possible carbon footprint before procurement begins. Such an approach, combined with advanced Building Information Modeling (BIM) software and Life Cycle Assessment (LCA), creates a reliable shield against managerial inefficiency. In addition, conducting a "Green Building Assessment", which goes beyond basic energy efficiency (e.g., ASHRAE Level 1) to include analysis of indoor air quality, waste reduction, and material sustainability, allows organizations to uncover hidden resource-saving reserves.

6. Conclusion

The transition of the construction sector to resource-saving and eco-oriented operational models represents one of the main challenges of the green economy era. The comprehensive analysis conducted in this study, combining international theoretical concepts with robust econometric tools (a three-stage SBM-DEA model, Stochastic Frontier Analysis SFA, and Tobit regression), revealed the deep mechanics of eco-efficiency formation in large construction enterprises.

First, the research reliably confirmed that traditional evaluation methods overestimate the actual efficiency of corporations. After purging the data of the favorable impact of macroeconomic variables (such as GDP and regional marketization level) and statistical noise, the industry's baseline managerial and technological eco-efficiency turned out to be quite modest (averaging around 0.73), indicating immense untapped potential for process optimization. A significant proportion of enterprises suffer from scale inefficiency and are in the stage of increasing returns, dictating the need to consolidate green investment projects to reduce transaction costs.

Second, it was found that the straightforward tightening of environmental regulation exerts a depressive effect on construction company productivity in the short term by increasing the financial burden and volume of production losses. However, this barrier is overcome through the integration of external incentives: pressure from environmentally conscious publics forces companies to invest in forming a "Green Corporate Image", which, under conditions of high market competition, translates into direct competitive advantages.

Third, Tobit regression analysis proved that strategic success in resource saving depends less on simply updating construction machinery (which often even increases emissions) than on the depth of integration with auxiliary industries—eco-design, consulting, and monitoring. It is precisely at the design stage, utilizing open global databases like the EC3 calculator, Bloomberg Terminal, and ESG analytics tools from Refinitiv Eikon, that genuine supply chain energy efficiency is formed.

To ensure long-term profitability and minimize their ecological footprint, it is recommended that large construction corporations focus on three key directions: first, radically transform the on-site energy consumption structure in favor of renewable sources; second, digitalize procurement processes, prioritizing materials with verified Environmental Product Declarations (EPDs); and third, ensure the absolute transparency of their non-financial ESG reporting to investors and society. Only a comprehensive strategy combining innovative materials, digital management, and ethical responsibility can guarantee the leadership of construction corporations within the realities of a global green economy.

References

[1] Zubair, M. U., et al. "Energy efficiency evaluation of construction projects using data envelopment analysis and Tobit regression." Scientific Reports.

[2] US Environmental Protection Agency (EPA). "ENERGY STAR and Green Building Materials."

[3] Nazir, T., & Afza, T. (2009). "Working Capital Management, Efficiency, and Tobit Analysis in the Manufacturing Sector."

[4] Kutlu. (2020). "Eco-efficiency of 35 sectors in Sweden by using an output-oriented Stochastic Frontier Analysis (SFA) model."

[5] Zinchenko, M., & Nazvanov, D. "Green Organizational Capabilities (GOC) for construction enterprises in Vietnam." Ways to Improve Construction Efficiency.

[6] Ismoilov, J. "Eco-innovation and resource-saving technologies as a factor of ecological sustainability."

[7] Chen, Y., et al. "Efficiency of Water Pollution Control Based on a Three-Stage SBM-DEA Model." Water.

[8] Evan et al. "DEA limitations and Green efficiency in construction."

[9] Zhu, Y., & Liu, H. "Three-stage SBM-DEA model and separation of environmental and random effects."

[10] Cullinane et al. "The impact of degree of marketization and environmental regulation intensity on green production efficiency."

[11] Wang, Z. (2024). "Efficiency of construction waste and carbon reduction in the construction industry based on improved three-stage SBM-DEA model in China." Engineering Construction & Architectural Management.

[12] Li, H., et al. "Enhancing eco-efficiency in China's construction industry: measurement, drivers and policy implications using an EBM-Tobit approach."

[13] Tobit regression framework for limited dependent variable DEA scores.

[14] OECD. "Eco-innovation, resource saving, and positive environmental impacts."

[15] Hermosilla et al. "Eco-innovation effects on recycling processes and per-unit resource utilization."

[16] EIO. "Resource-efficient construction, dematerialization, and Nanotechnology in buildings."

[17] Greene. "Economic and environmental efficiency of Asian and African economies using Translog production function."

[18] "Carbon emission efficiency evaluation of 55 publicly listed Chinese construction enterprises from 2017 to 2022.", Greene. "Economic and environmental efficiency of Asian and African economies using Translog production function." "The Impact of Environmental Public Opinion Pressure on Green Innovation: The Mediating Role of Green Corporate Image (GCI)."