Integrated ABC–TOC Framework for Comparing Five Multi-Period Carbon-Pricing Models

Archit Jain[1, *], Rajkumar [2, a], Shiv Raj Singh (Professor)[3], Lakhan Singh (Professor)[4], Rajiv Kumar (Professor)[5]

[1,2,4,5] Institute- Department of Mathematics, Digambar Jain College, Baraut, UP, India
[3] Institute- Department of Mathematics, Ch. Charan Singh University, Meerut, UP, India
*Corresponding author

[a] Department of Mathematics, S.U.S. Govt. College, Matak Majri, Karnal, Haryana
Email- [1] architjain1610@gmail.com ; [2] rajkuk7414@gmail.com ;
[3] shivrajsingh@ccsuniversity.ac.in ; [4]drlakhansingh10@gmail.com ;
[5] rajiv73kr@gmail.com ;

ABSTRACT

The cement industry is one of the largest producers of carbon dioxide emissions and thus needs production-planning models that produce profit while simultaneously being environmentally sustainable. This study presents an integrated optimization method of Activity Based Costing(TOC) to analyse the impact of carbon tax, tax exemptions, emissions trading, environmental, social and governance requirements, and production-resource constraints on optimisation of cement manufacturing decisions. Five carbon-pricing models are developed. These models are: continuous incremental progressive carbon-tax structure, tax-exemption mechanism, emissions-trading mechanism, combined tax-exemption and emissions-trading mechanism, and discontinuous incremental progressive carbon-tax structure. The models include raw-material costs, labour costs, operational costs, fixed costs, carbon-emission costs, production capacity, other raw-material usage, and carbon-emission restrictions. LINGO 20 is used to calculate the best product mix and to analyse the profitability and environmental effects in the five policy scenarios. It is found that the total profit in the results of the model 3 is $22.74486 billion, the highest total profit among all of the models. The models can also be used to help target a reduction in the carbon-emission ratio and help with the progressive use of alternative materials. Based on sensitivity analysis, the higher the rate of the carbon tax, the more likely the profitability of the models will decrease. The proposed framework offers a pragmatic decision support tool for both cement manufacturers and policy makers who are aiming to navigate the trade-offs between profitability, emissions, resource efficiency, and ESG performance.

Keywords: Carbonation; Emissions; Taxation; Trading; Sustainability; Optimization

1. INTRODUCTION

The rapid economic and industrial development has brought on environmental issues like greenhouse gas emission, air pollution, and consumption of natural resources. This has led to an increased focus of governments, investors, industries and communities on environmental responsibility in the corporate world. Environmental impacts become a key part of the regulatory landscape, company image and reputation, the investment climate, and the long-term competitiveness of industrial enterprises. This has led to the incorporation of Environmental, Social and Governance (ESG) principles in corporate planning becoming an important strategic priority [1]. To date, however, there are only few sector-specific decision-support models which address environmental policies, production limitations and financial outcomes in carbon intensive sectors together [2].

In this regard, cement industry is one of the most relevant sectors as it is associated with significant CO2 emissions and energy consumption during cement production [3]. Emissions include those from burning fuels, and also emissions from the calcination of limestone. Calcium Carbonate (CaCO3) undergoes calcination to produce Calcium Oxide (CaO) and Carbon Dioxide (CO2) which is inevitable in the process [4]. So the impacts of carbon taxes and emissions trading on policy decisions regarding cement production are of significant policy and practical interest [5].

In this study, the authors analyse the profitability, production planning, carbon cost and ESG performance of the cement manufacturers under various carbon pricing regimes [6]. It compares and analyzes five multi-period models that combine different emission taxes, emissions allowances, tax exemption, and discontinuous tax systems. The aim is to determine the best combination of products for the greatest profit when considering carbon cost, resource constraints, alternative material needs, and emissions reduction goals. The activity-based costing (ABC) is used to make more accurate cost allocation by assigning the cost of raw materials, labour, operations and environment to the activities, and products that create them [17,18]. Theory of Constraints is used to find production constraints and environmental constraints that hinder the performance of an organisation [19]. The use of ABC and TOC therefore sets a good framework for analysing the effects of cost drivers and resource limitations on the optimality of production decisions.

A carbon tax can be imposed on the emissions of GHGs and incentivize companies to either cut emissions or adopt new technologies that help the companies to reduce emissions [10,11]. Emissions trading is another market-based tool for trading carbon credits based on their emissions position. The economic basis for emissions trading is linked to the efficient allocation of the emission rights with clearly defined property rights and low transactions costs [12,13]. However, few studies have done a multi-treatment comparison of several different carbon-tax and emissions-trading regimes in a sector-specific optimization program [14].

ESG performance goes beyond financial results to include the social, environmental and governance practices of a company [15]. The environmental indicators that are relevant to cement manufacturers are carbon-emission intensity and the use of alternative materials. The current study, therefore, takes the progressively lowering carbon-emission limits and rising requirement for alternative materials into the optimization framework. The proposed ABC – TOC framework is designed to differ from traditional profit maximisation approaches, by taking into account product revenues, activity-related costs, carbon pricing mechanisms, ESG targets and production constraints. ABC offers a detailed cost information, and TOC describes the constraints which affect product-mix and resource-allocation decisions. The study offers evidence on the financial and environmental outcomes of operating a cement plant across five policy options through a comparison.

The mathematical programming models are solved using LINGO 20, and the product mix which maximizes the total profit within the developed constraints is identified. The model takes four product categories into account and includes revenues, raw-material usage, labour costs, operational activities, machine capacity, the costs for carbon emissions, fixed costs, production needs, and ESG costs. Solutions obtained are then compared with respect to the total profit, carbon cost, emission performance and utilization of resources. The sensitivity analysis also considers the impact of varying prices on the profitability. This analysis is required due to the potential for carbon prices to change as a result of regulatory changes, inflation, political decisions, market conditions, or national climate commitments. [32] The study compares policy structures with different unit carbon-tax costs by keeping other parameters fixed to identify which policy structures are more sensitive to changes in the carbon tax. This is informative for both manufacturers and policy makers about the financial viability of alternative methods of carbon pricing.

The main purpose of this study is to create an integrated decision-support system for investigating the effect of various carbon-pricing policies on the profitability of cement manufacturers and environmental impacts. Specifically, the study aims at:

1. Propose an integrated framework of ABC-TOC solution in multi-period cement-production planning;
2. Compare five alternate models of carbon tax, tax exemption and emissions trading;
3. Calculate the maximum product mix and overall profit for each policy situation; and
4. Assess the impacts of carbon pricing on carbon-emission costs and ESG measures;
5. Evaluate the declining carbon-emission ratio and the growing preference for other materials; and
6. examine the sensitivity of profitability to changes in carbon-tax rates.

The study has several contributions to make. It brings together management accounting, production constraints, carbon taxation, emission trading, and ESG together in one mathematical framework. Second, it compares five different possible configurations of carbon pricing within a single country, at the firm level, and does not consider a single tax structure. Third, it includes multi-period environmental targets reflecting the fact that emissions reduction and resource substitution is a process. In addition, it illustrates the direct incorporation of carbon costs into product-mix decisions. Last but not least, it offers a practical analytical tool to help cement companies achieve a balance between profitability, environmental compliance, resource efficiency, and sustainability for long-term success. The results are also applicable to policy makers. Carbon-pricing policies might have unintended economic effects or not be able to provide environmental benefits if they do not take into account the constraints on firm production. The model can help policy-makers evaluate if tax exemptions, progressive rates, or emissions-trading schemes are sufficiently firm but also flexible enough to achieve a balance to achieve an optimal policy structure.

This study tackles the challenges of creating an operationally comprehensive and environment friendly decision model in the cement sector. It integrates the various aspects of taxation, trading, costing and production constraints within a unified optimization framework, overcoming the limitation of the traditional approach that treats them as separate evaluations. The resulting analysis also yields evidence of the impact of carbon-pricing policies on production decisions and the policy setup that offers the highest likelihood of achieving a favourable profitability outcome with the necessary emissions-reduction and alternative-material goals.

2. RESEARCH METHODS

2.1. Cement Production Process and ESG Indicators

Figure 1 shows a broad view of the cement manufacturing process, highlighting all the essential steps: raw material grinding (m = 1), the calcination process (m = 2), grinding of cement (m = 3) and the three different stages of batching (m = 4, m = 5, m = 6). A great step forward in this process is the use of 'waste' from different industries as raw materials. The high temperatures, high turbulence and long retention time in the calcination phase of the process (m = 2) are effective in the treatment of the waste material [21]. As a result of the calcination process valuable byproducts are generated such as sludge and slag, as well as essential elements to be re-introduced to the manufacturing chain, such as silicon, aluminium, iron and calcium. This approach not only assists in the management of waste but also plays a significant role in lowering expenses, thereby enhancing the overall efficiency and sustainability of the process.

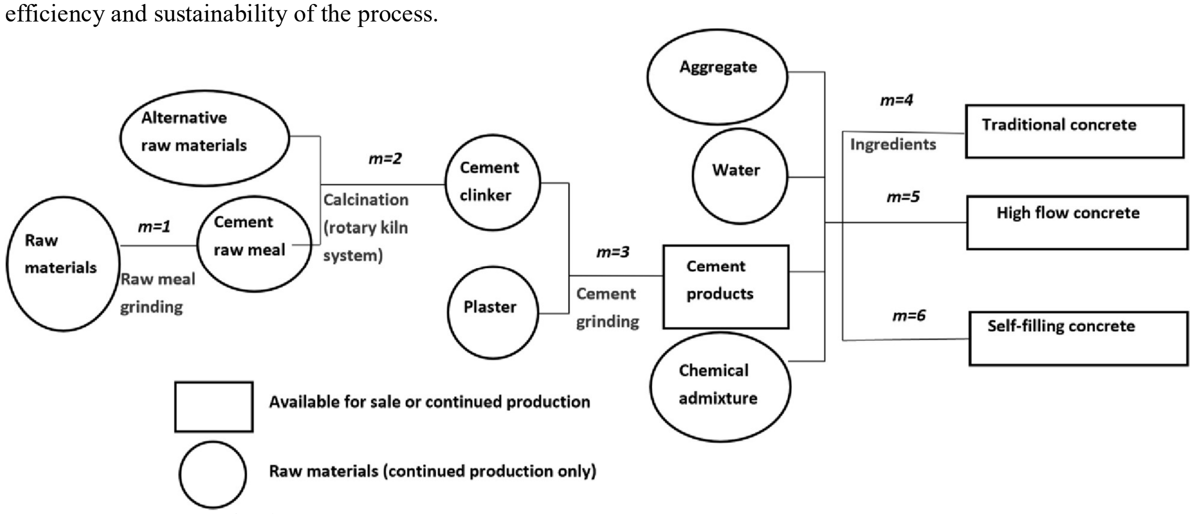

Figure 1. Cement Production Process.

This research sets these different targets for the timeframe 2023-2025 with the aim of reducing greenhouse gas emissions and improving resource recycling processes. The goals to reduce GHG emissions focus on the CO_2 emissions from the production of cementitious materials per tonne of product, based on the 2016 reference. While the targets for the years 2023 and 2024 have not been set, it is clear that the target for 2025 is set to be an 11% reduction. The research sets a specific number of tonnes to be recycled: 1.14 million tonnes in 2023, to be followed by 1.2 million tonnes in 2024 and 1.25 million tonnes in 2025. These goals represent a strategic move towards more sustainable farming practices.

The basic ESG related indicators from the cement sustainability report have been used in the analysis [22]. Emphasis is given to reducing carbon dioxide emissions and using alternative materials to produce the goods. The framework employs the Theory of Constraints to methodically diminish CO2 emissions each year, all the while enhancing the utilisation of alternative materials. This strategy seeks to harmonise with ecological sustainability, minimise carbon emissions, and enhance resource utilisation, showcasing a dedication to enduring industrial methodologies.

2.2. Research Assumptions

The cement industry will be used as a case study to investigate the cost impacts of carbon taxes and carbon credits (carbon rights) on financial results of corporations and ESG indicators. In the combination of the ACTIVITY BASED COSTING and the THEORY OF CONSTRAINTS, a thorough decision making process for production in the organization is created [24]. Then, mathematical programming methods are used to examine the effects of the carbon tax and the cost of the carbon credits on the environmental, social and governance (ESG) indicators and profits. The following assumptions are made for the purpose of eliminating the influence of any uncontrollable external factors:

The unit prices remain constant during the manufacturing process, while the cement price (i = 1), concrete price (i = 2), high-fluidity concrete price (i = 3), and the self-compacting concrete price (i = 4) are the main products manufactured by the organization.

A total of seven primary raw materials are utilised: Clinker (j = 1), Gypsum (j = 2), alternative materials (j = 3), Cement (j = 4), Aggregates (j = 5), Water (j = 6), and Pyrite (j = 7). The expenses of these materials cost the same throughout production.

Incorporating waste from different industries, waste products become an alternative such as sludge, slag (si, al, fe, ca), components etc are used as basic resources. This will not only help to make waste management easier but also help to save money.

The use of alternatives to materials is considered an important ESG indicator for the organization, and the amount of these alternatives will be increased annually, which will lead to the goal of “Net Zero Emissions by 2050.”

Along the manufacturing process, each of the manufacturing stages are classified at the unit-level, batch-level and product-level.

Overtime work is allowed as per the procedure and policy and overtime pay is admissible in accordance with the applicable overtime rates as per the procedure and policy by personnel from human resources department. In

addition, all equipment and human resources are operated at 100% efficiency with no idle equipment and labour is paid the same amount throughout the production process.
There is a carbon tax on the production of each individual unit of product, so that the cost of the tax depends on the number of units produced.
The cost of trading carbon credits is expected to be negligible for individual companies, while the limitations on carbon credit trading will be determined by governmental rules that are likely to remain unchanged over the next few years.
The amount of carbon emission reduction (tons of CO2 per ton of binder material) is steadily increasing every year in line with the goal of becoming "Net Zero Emissions by 2050".

2.3 Objective Function

2.3.1. General Formula for the Objective Function

The objective is to maximize profit (π). This is calculated as the total revenue from cement and concrete sales minus the total costs, which include direct material costs, direct labor costs, batch-level operational costs, product-level operational costs, carbon emission costs, and fixed expenses. To maximize profit (π), the formula is defined as follows [23]:

π = Total Revenue from Cement and Concrete Sales − Total Direct Material Costs − Total Direct Labor Costs
−Total Batch − Level operational Costs − Total Product − Level operational Costs
−Total Carbon Emission Costs − Total Fixed Costs

The general form of a multi-period objective function might be expressed as:

$$\pi = \sum_{t=1}^{3}\sum_{i=1}^{4} P_i X_{it} - \sum_{t=1}^{3}\sum_{i=1}^{4}\left(\sum_{j=1}^{7} MC_j MQ_{ijt}\right) X_{it}$$

$$-\sum_{t=1}^{3}[CDL_0 + \eta_{1t}(CDL_1 - CDL_0) + \eta_{2t}(CDL_2 - CDL_0)]$$

$$-\sum_{t=1}^{3}\left(\sum_{i=1}^{4}\sum_{m=4}^{6} BLC_m \alpha_{im} q_{imt}\right) - \sum_{t=1}^{3}\left(\sum_{i=1}^{4}\sum_{m=4}^{6} PLC_m \mu_{im} \Gamma_{it}\right)$$

$$-\sum_{t=1}^{3} CarbonTax - \sum_{t=1}^{3} F_t\,(FixedCost)$$

These definitions provide a structured framework for the mathematical modeling of the cement production process, taking into account various factors like product types, raw materials, production processes, and temporal dynamics.

i Product index where $i = 1$ to 4. Products are: $i = 1$ (Finished Cement), $i = 2$ (Traditional Concrete), $i = 3$ (High Fluidity Concrete), $i = 4$ (Self-compacting Concrete).
j Raw material index where $j = 1$ to 7. Raw materials are: $j = 1$ (Clinker), $j = 2$ (Gypsum), $j = 3$ (Alternative Materials), $j = 4$ (Cement), $j = 5$ (Aggregates), $j = 6$ (Water), $j = 7$ (Chemical Additives).
m Process index where $m = 1$ to 6. Processes are: $m = 1$ (Raw Meal Grinding), $m = 2$ (Calcination), $m = 3$ (Cement Grinding), $m = 4, m = 5, m = 6$ (Batching).
t Time period index where $t = 1$ to 3.
P_i Unit price of the i^{th} product for different time periods ($t = 1,2,3$).
X_{it} Quantity of the i^{th} product in period t ($i = 1 \sim 4; t = 1 \sim 3$).
MQ_{ijt} Quantity of the j^{th} raw material required for producing one unit of the i^{th} product during the t^{th} time period ($i = 1 \sim 4; j = 1 \sim 7; t = 1 \sim 3$).
CDL_0
CDL_1 Total direct labor costs at points CDL_0, CDL_1 and CDL_2 respectively.
CDL_2
η_{1t}, η_{2t} Non-negative variables for period t, with at most two adjacent variables being non-zero ($t = 1 \sim 3$).
BLC_m Unit batch-level cost in the m^{th} process ($m = 3 \sim 6$).
α_{im} Resource consumption per batch for the i^{th} product in the m^{th} batch-level process ($= 1 \sim 4; m = 3 \sim 6$).
q_{imt} Number of batches for the i^{th} product in the m^{th} process during period t ($i = 1 \sim 4$;

$m = 3 \sim 6; t = 1 \sim 3$).
β_{im}Number of batches for the i^{th} product in the m^{th} batch-level process ($i = 1 \sim 4$; $m = 3 \sim 6$).
PLC_mUnit product-level cost in the m^{th} process ($m = 3 \sim 6$).
μ_{im}Resource consumption for the i^{th} product in the m^{th} product-level process ($i = 1 \sim 4$; $m = 3 \sim 6$).
Γ_{it}Binary variable for period t, determining whether the i^{th} product is produced (1 if produced, 0 otherwise) ($i = 1 \sim 4; t = 1 \sim 3$).
F_tTotal fixed cost in period t ($t = 1 \sim 3$).

2.3.2. Direct Material Cost Function

This study assumes cement producers primarily use seven raw materials: clinker ($j = 1$), gypsum ($j = 2$), alternative materials ($j = 3$), cement ($j = 4$), aggregates ($j = 5$), water ($j = 6$), and Pyrite ($j = 7$). In the multi-period model, the usage of alternative materials ($j = 3$)will be progressively increased each year to meet the ESG targets by 2025, with the direct costs of these materials factored into the profit function.
With constraints:

$$\sum_{i=1}^{4}(M\,Q_{ijt}X_{it}) \le UBMQ_{jt}(j = 1 \sim 7; t = 1 \sim 3)(1)$$

$$\sum_{i=1}^{4}(M\,Q_{ijt}X_{it}) \ge LBMQ_{jt}(j = 1 \sim 7; t = 1 \sim 3)(2)$$

Symbol Definitions:

MC_jUnit cost of the j^{th} raw material, ($j = 1 \sim 7$)
MQ_{ijt}Quantity of the j^{th} raw material required per unit of the i^{th} product ($i = 1 \sim 4; j = 1 \sim 7$; $t = 1 \sim 3$)
$UBMQ_{jt}$Upper limit on the available quantity of the j^{th} raw material in period t ($j = 1 \sim 7$; $t = 1 \sim 3$)
$LBMQ_{jt}$Lower limit on the available quantity of the j^{th} raw material in period t ($j = 3; t = 1 \sim 3$)

2.3.3. Direct Labor Cost Function

In the cement production process, direct labor, including regular and overtime hours, is a key component. This study assumes that the total direct labor cost function is a continuous piecewise linear function, as illustrated in Figure 2. If the required direct labor hours exceed regular working hours, two different wage rates are applied for the two types of labor hours. It's assumed that the wage rates for each segment in Figure 2 are WR_0, WR_1,and WR_2,representing different rates for varying work hour segments [25].

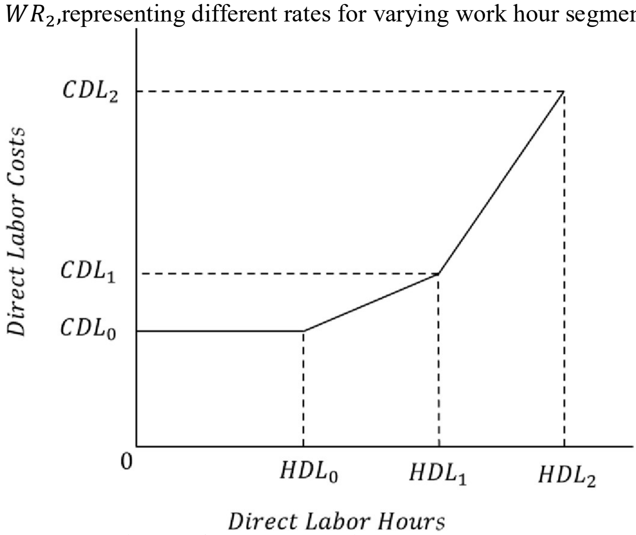

Figure 2. Direct Labor Cost Function.

Associated constraints for the labor cost function are also defined:

$$\sum_{i=1}^{4}\sum_{m=1}^{6}(HR\,L_{im})X_{it} \le HDL_0 + \eta_{1t}(HDL_1 - HDL_0) + \eta_{2t}(HDL_2 - HDL_0)(3)$$

$\eta_{0t} - \Omega_{1t} \leq 0(4)$
$\eta_{1t} - \Omega_{1t} - \Omega_{2t} \leq 0(5)$
$\eta_{2t} - \Omega_{2t} \leq 0(6)$
$\eta_{0t} + \eta_{1t} + \eta_{2t} = 1(7)$
$\Omega_{1t} + \Omega_{2t} = 1(8)$
$\Omega_{1t}, \Omega_{2t} = 0{,}1(9)$
$0 \leq \eta_{0t}, \eta_{1t}, \eta_{2t} \leq 1(10)$
$t = 1 \sim 3$

Symbol Definitions:

X_{it}Quantity of the i^{th} product in period t, $(i = 1 \sim 4; t = 1 \sim 3)$
$\eta_{0t}, \eta_{1t}, \eta_{2t}$Non-negative variables where at most two adjacent variables are not 0, $(t = 1 \sim 3)$
Ω_{1t}, Ω_{2t}Dummy variables $(0,1)$, where only one can be 1 for each period $(t = 1 \sim 3)$
HRL_{im}Labor hours required to produce one unit of the i^{th} product in the m^{th} process.
HDL_0The total number of labor hours under normal circumstances
HDL_1Maximum number of labor hours falling in the first overtime segment, as shown in Figure 2
HDL_2Maximum number of labor hours in the second overtime segment, as indicated in Figure 2

2.3.4. Batch-Level Operational Costs

It's assumed that four operational activities in the cement production process require estimation of machine handling costs: cement grinding $(m = 3)$and three batching processes $(m = 4, m = 5, m = 6)$. These costs are deducted in the profit function [26].
The related constraint functions are:

$$X_{it} \leq \beta_{im} q_{imt} (i = 1 \sim 4; m = 3 \sim 6; t = 1 \sim 3)(11)$$

$$\sum_{i=1}^{4} \alpha_{im}\, q_{imt} \leq R_m (m = 3 \sim 6; t = 1 \sim 3)(12)$$

Symbol Definitions:

BLC_mUnit machine handling cost for the m^{th} process
α_{im}Resource consumption per batch for the i^{th} product in the m^{th} process $(i = 1 \sim 4;$ $m = 3 \sim 6)$
β_{im}Output per batch for the i^{th} product in the m^{th} process $(i = 1 \sim 4; m = 3 \sim 6)$
R_mMaximum available resources for the m^{th} batch-level operation $(m = 3 \sim 6)$

3.3.5. Product-Level Operational Costs

It is assumed that product-level operation costs, specifically for product batching, need to be estimated for four activities: cement grinding $(m = 3)$and three batching processes $(m = 4, m = 5, m = 6)$. These product batching costs are subtracted from the profit function.
Constraint inequality includes:

$$\sum_{i=1}^{4} \mu_m\, \Gamma_{it} \leq P_m (m = 3 \sim 6; t = 1 \sim 3)(13)$$

Symbol Definitions:

PLC_mUnit cost of product batching for the m^{th} process
μ_{im}Resource consumption for the i^{th} product in the m^{th} process $(i = 1 \sim 4; m = 3 \sim 6)$
Γ_{it}Dummy variable $(0,1)$ for period t, determining whether the i^{th} product is produced $(i = 1 \sim 4; t = 1 \sim 3)$
P_mMaximum available resources for the m^{th} product-level operation $(m = 3 \sim 6)$

3.3.6. Constraints of Machine Hours

It's assumed that three types of automated equipment are used in the manufacturing process: raw meal grinding $(m = 1)$, calcination $(m = 2)$, and cement grinding $(m = 3)$, replacing traditional manual labor to enhance efficiency.
The related constraint inequality for machine hours is:

$$\sum_{i=1}^{4} M\,H_{im} X_{it} \leq LMH_m (m = 1 \sim 3; t = 1 \sim 3)(14)$$

Symbol Definitions:

MH_{im} Machine hours required to complete one unit of the i^{th} product in the m^{th} process ($m = 1 \sim 3$)

LMH_m Upper limit of available machine hours for the m^{th} process ($m = 1 \sim 3$)

2.4. Carbon Tax Cost Function Model

2.4.1. Model 1: Continuous Incremental Progressive Tax Rate Function for Carbon Tax

This study develops a model for a continuous incremental progressive carbon tax function for the cement industry. The cost functions for multiple periods are designed to optimize profit while considering carbon tax expenses. The models are summarized as follows [27]:

Figure 3 shows the function of carbon tax cost in the continuous incremental progressive tax rate. In Figure 3, the upper limit of carbon emission quantity in the first, second and third sections is CEQ_1, CEQ_2 and CEQ_3, the carbon tax costs at the three points of CEQ_1, CEQ_2 and CEQ_3 are CT_1, CT_2 and CT_3 respectively, and the carbon tax rates are TR_1, TR_2 and TR_3 respectively.

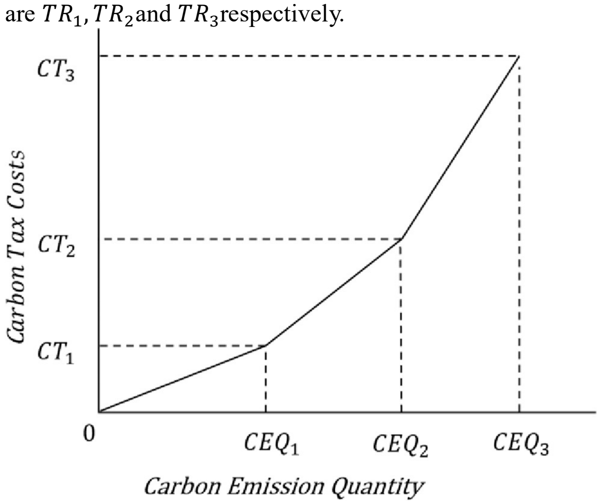

Figure 3. Carbon Tax Costs Function with Progressive Rates.

General expression of carbon tax cost function in Figure 3 is shown as follows:

$$f(q)=\begin{cases} q * TR_1, if 0 & ; \leq q \leq CEQ_1 \\ CT_1 + (q - CEQ_1)TR_2, if CE & ; Q_1 < q \leq CEQ_1 (15) \\ CT_2 + (q - CEQ_2)TR_3, if CE & ; Q_1 < q \end{cases}$$

The general formula of the carbon tax cost function (15) is derived from this representation. It is a function of the company's total carbon emissions (q) and is applied in a mathematical programming model. The model includes assumed carbon tax costs function (16), which are deducted from the company's total profit, along with related restrictions (17)–(25).

Multi-Period Carbon Tax in Objective Function:

$$\sum_{t=1}^{3} C\,T_i = CT_1 v_{1t} + CT_2 v_{2t} + CT_3 v_{3t} (16)$$

Related Constraints:

$$\sum_{i=1}^{4} \sum_{m=1}^{6} C\,E_{im} X_{it} = CEQ_1 v_{1t} + CEQ_2 v_{2t} + CEQ_3 v_{3t} (17)$$

$$v_{0t} - \omega_{1t} \leq 0 (18)$$
$$v_{1t} - \omega_{1t} - \omega_{2t} \leq 0 (19)$$
$$v_{2t} - \omega_{2t} - \omega_{3t} \leq 0 (20)$$
$$v_{3t} - \omega_{3t} \leq 0 (21)$$
$$v_{0t} + v_{1t} + v_{2t} + v_{3t} = 1 (22)$$
$$\omega_{1t} + \omega_{2t} + \omega_{3t} = 1 (23)$$
$$0 \leq v_{0t}, v_{1t}, v_{2t}, v_{3t} \leq 1 (24)$$

$$\omega_{1t}, \omega_{2t}, \omega_{3t} = 0,1(25)$$
$$t = 1 \sim 3$$

In the example, the total optimized profit across three periods ($t = 1$ to 3) amounts to \$22,473,270,000. The profit is highest in the initial period, with subsequent periods showing a decline due to increased use of alternative materials and stricter carbon emission limits. The model also captures a decreasing trend in carbon emission ratios $CER_1$to CER_3over the considered timeframe [28].

2.4.2. Model 2: Continuous Incremental Progressive Carbon Tax Function with Tax Exemption

Model 2 of the study considers continuous incremental progressive carbon tax function with tax exemption. The carbon tax cost function of the progressive tax rate for continuous allowance increase is illustrated in Figure 4. In this figure, CEQ_0represents the total carbon emissions granted by the government for tax exemption, which are not subject to taxation within the carbon emission allowance. The first, second, and third interval have a capped carbon emission quantity at $CEQ_1, CEQ_2$and CEQ_3respectively. $CT_1, CT_2$and CT_3denote the cost of carbon tax at these respective levels while $TR_1, TR_2$and TR_3represent their corresponding tax rates.

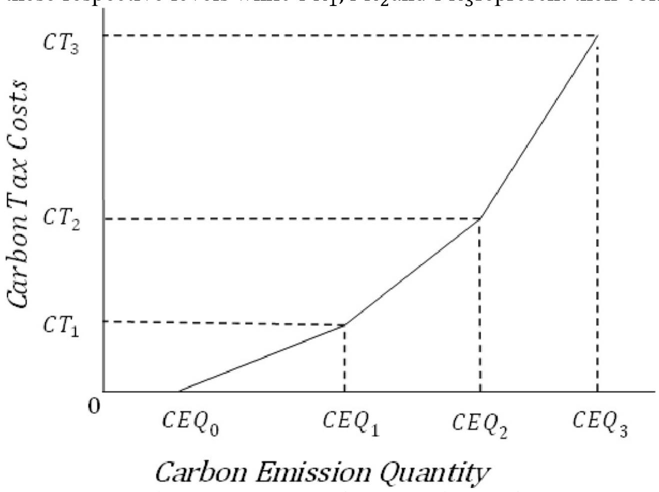

Figure 4. Continuous Incremental Progressive Carbon Tax Function with Tax Exemption.

Henceforth, we can express the carbon tax cost function in Figure 4 as function (26), which serves as a general formula encompassing continuous carbon tax costs with allowances. When calculating the company's overall profit, it is necessary to deduct the assumed carbon tax costs specified by (27) and (28) in this model. Constraints related to the cost of carbon taxes are defined by (28)–(36).

The general formula for the carbon tax cost function is:

$$f(q) = \begin{cases} 0, if\, 0 & ; \le q \le CEQ_0 \\ (q - CEQ_0)TR_1, if\ CE & ;\ Q_0 < q \le CEQ_1 \\ CT_1 + (q - CEQ_1)TR_2, ifCE & ;\ Q_1 < q \le CEQ_2 \\ CT_2 + (q - CEQ_2)TR_3, ifCE & ;\ Q_2 < q \end{cases} \quad (26)$$

In a multi-period scenario, the function is defined in the objective function as:

$$\sum_{t=1}^{3} C\,T_i = CT_1\varepsilon_{1t} + CT_2\varepsilon_{2t} + CT_3\varepsilon_{3t}(27)$$

The related constraints for the carbon tax cost function are:

$$\sum_{i=1}^{4} \sum_{m=1}^{6} C\,E_{im}X_{it} \le CEQ_0 + (CEQ_1 - CEQ_0)\varepsilon_{1t} + (CEQ_2 - CEQ_0)\varepsilon_{2t}$$
$$+(CEQ_3 - CEQ_0)\varepsilon_{3t}(28)$$
$$\varepsilon_{0t} - \omega_{1t} \le 0(29)$$
$$\varepsilon_{1t} - \omega_{1t} - \omega_{2t} \le 0(30)$$
$$\varepsilon_{2t} - \omega_{2t} - \omega_{3t} \le 0(31)$$
$$\varepsilon_{3t} - \omega_{3t} \le 0(32)$$
$$\varepsilon_{0t} + \varepsilon_{1t} + \varepsilon_{2t} + \varepsilon_{3t} = 1(33)$$
$$\omega_{1t} + \omega_{2t} + \omega_{3t} = 1(34)$$

$0 \leq \varepsilon_{0t}, \varepsilon_{1t}, \varepsilon_{2t}, \varepsilon_{3t} \leq 1 (35)$
$\omega_{1t}, \omega_{2t}, \omega_{3t} = 0,1 (36)$
$t = 1 \sim 3$

The total best profit for the enterprise over several periods is \$22,506,340,000 of which the highest profit is in the first period. The second and third periods have lower profits because alternative materials' lower limits are taken into account and carbon emissions' upper limits are not. Moreover, it is evident that the carbon emission ratio shows a downtrend over time [29].

2.4.3. Model 3: Continuous Incremental Progressive Carbon Tax Function with Carbon Trading

If the government permits carbon trading, then the costs and benefits of carbon credits should also be taken into account, in addition to the carbon tax costs. This section builds upon the continuous incremental progressive carbon tax cost function of Section 2.4.1, and extends the model assumptions to include carbon trading functions. This study assumes that the company uses a single carbon credit price (α)to purchase or sell carbon credits. Thus, the cost function of carbon tax (plus the cost of carbon credit) is (37) for continuous incremental progressive carbon tax.

The multi-period carbon tax objective function, with carbon trading, is formulated as follows:

$$\sum_{t=1}^{3} C\,T_i = \left[\sum_{t=1}^{3}(CT_1 v_{1t} + CT_2 v_{2t} + CT_3 v_{3t}) - \alpha(MCEQ - \textstyle\sum_{t=1}^{3} q_t)\right]\sigma_1 + \left[\sum_{t=1}^{3}(CT_1 v_{1t} + CT_2 v_{2t} + CT_3 v_{3t}) + \alpha(\textstyle\sum_{t=1}^{3} q_t - MCEQ)\right]\sigma_2 (37)$$

The related constraints are as follows:

$$q_t = \sum_{i=1}^{4}\sum_{m=1}^{6} C\,E_{im}X_{it} = \Lambda_1 + \Lambda_2 (38)$$

$0 \leq \Lambda_1 \leq \sigma_1 MCEQ (39)$
$\sigma_2 MCEQ < \Lambda_2 \leq \sigma_2 MPCEQ (40)$
$\sigma_1 + \sigma_2 = 1 (41)$
$t = 1 \sim 3$

With the multi-period continuous incremental progressive carbon tax function and the carbon trading (Model 3), the optimal profit is \$22,744,860,000. Incorporating carbon credits into profit function, as in Model 1 [30] the profits are higher.

2.4.4. Model 4: Continuous Incremental Progressive Carbon Tax Objective Function

The assumptions are build on the continuous incremental progressive carbon tax cost function from Section 2.4.1 and include the tax exemption provided by the government from Section 2.4.2 and carbon trading from Section 2.4.3. It is hypothesized that the company trades carbon at one carbon credit price (α) and thus the incremental progressive carbon tax cost function is now written as (42) plus the cost of carbon tax exemption.

The multi-period model continuous incremental progressive carbon tax cost function with tax exemption and carbon credits is:

$$\sum_{t=1}^{3} C\,T_i = \left[\sum_{t=1}^{3}(CT_1 \varepsilon_{1t} + CT_2 \varepsilon_{2t} + CT_3 \varepsilon_{3t}) - \alpha(MCEQ - \textstyle\sum_{t=1}^{3} q_t)\right]\sigma_1 + \left[\sum_{t=1}^{3}(CT_1 \varepsilon_{1t} + CT_2 \varepsilon_{2t} + CT_3 \varepsilon_{3t}) + \alpha(\textstyle\sum_{t=1}^{3} q_t - MCEQ)\right]\sigma_2 (42)$$

The related constraints are as follows:

$$q_t = \sum_{i=1}^{4}\sum_{m=1}^{6} C\,E_{im}X_{it} = \Lambda_1 + \Lambda_2 (43)$$

$0 \leq \Lambda_1 \leq \sigma_1 MCEQ (44)$
$\sigma_2 MCEQ < \Lambda_2 \leq \sigma_2 MPCEQ (45)$
$\sigma_1 + \sigma_2 = 1 (46)$

$$t = 1 \sim 3$$

2.4.5. Model 5: Discontinuous Incremental Progressive Carbon Tax Objective Function

Figure 5 illustrates the carbon tax cost function for a discontinuous incremental progressive tax rate, composed of three consecutive sections. In Figure 5, the maximum carbon emission limits for the first, second, and third sections are $CEQ_1, CEQ_2$and CEQ_3, respectively. The carbon tax rates at these points are TR_1, TR_2,and TR_3, and the carbon tax costs are calculated as TR_1CEQ_1, TR_2CEQ_2,and TR_3CEQ_3, respectively.

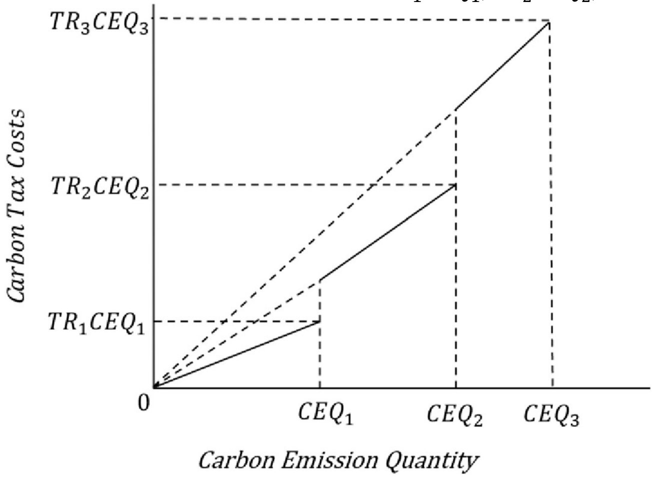

Figure 5. Discontinuous Carbon Tax Cost.

So, the cost function of carbon tax in Figure 5 can be written as functions (47). This function represents the general form of the cost function for the discontinuous carbon tax and it also represents the total carbon emissions (q) of a company, which can be modeled mathematically. The carbon tax costs assumed in this model is function (48) and constraints relating to carbon tax costs are (49) to (54) [31].

General Expression of Cost Function of Carbon Tax:

$$f(q)=\begin{cases} 0, if\, 0 & ;\ \le q \le CEQ_0 \\ (q-CEQ_0)*TR_1, if\ CE & ;\ Q_0 < q \le CEQ_1 \\ (q-CEQ_1)*TR_2, if\ CE & ;\ Q_1 < q \le CEQ_2 \\ (q-CEQ_2)*TR_3, ifCE & ;\ Q_2 < q \end{cases} \quad (55)$$

Multi-Period Discontinuous Incremental Progressive Carbon Tax Cost Function:

$$\sum_{t=1}^{3} C\,T_i = \sum_{t=1}^{3} (T\,R_1EQ_{1t} + TR_2EQ_{2t} + TR_3EQ_{3t})(48)$$

Related Constraints:

$$\sum_{i=1}^{4} \sum_{m=1}^{6} C\,E_{im}X_{it} = EQ_{1t} + EQ_{2t} + EQ_{3t}(49)$$

$$0 \le EQ_{1t} \le \phi_{1t}CEQ_1(50)$$
$$\phi_{2t}CEQ_1 < EQ_{2t} \le \phi_{2t}CEQ_2(51)$$

$$EQ_{3t} > \phi_{3t}CEQ_2(52)$$
$$\phi_{1t} + \phi_{2t} + \phi_{3t} = 1(53)$$
$$\phi_{1t}, \phi_{2t}, \phi_{3t} = 0{,}1(54)$$
$$t = 1 \sim 3$$

3. RESEARCH RESULTS AND ANALYSIS

3.1. Model Comparison

This section compares the optimal solutions generated by five multi-period carbon-tax models under the specified production, resource, carbon-emission, and ESG constraints. Models 1–4 employ a continuous incremental progressive carbon-tax structure, while Model 5 employs a discontinuous incremental progressive carbon-tax structure. The continuous models differ according to the inclusion of tax exemption and carbon-trading provisions. Model 1, representing the basic continuous incremental progressive carbon-tax structure, generated a total optimal profit of **$22,473,270,000**. Model 2, which incorporates a carbon-tax exemption, generated a slightly higher profit of **$22,506,340,000**. Model 3, which incorporates carbon trading, reported an optimal profit of **$22,744,860,000**. The results for Models 4 and 5 should be inserted directly from the corresponding LINGO outputs.

The comparison indicates that carbon-pricing design influences the financial performance of the cement manufacturer. The inclusion of a tax exemption in Model 2 provides limited financial relief compared with Model 1, while the incorporation of carbon trading in Model 3 produces a more noticeable improvement in profitability. Model 4 evaluates the combined effects of tax exemption and carbon trading under the continuous tax structure, whereas Model 5 provides a comparison with a basic discontinuous incremental progressive carbon-tax structure. However, because Model 5 is the only discontinuous model included in the revised analysis, the results cannot provide a comprehensive comparison between continuous and discontinuous taxation systems. The findings should therefore be interpreted primarily as a comparison of policy mechanisms within the continuous progressive tax structure, supplemented by an initial discontinuous-tax scenario.

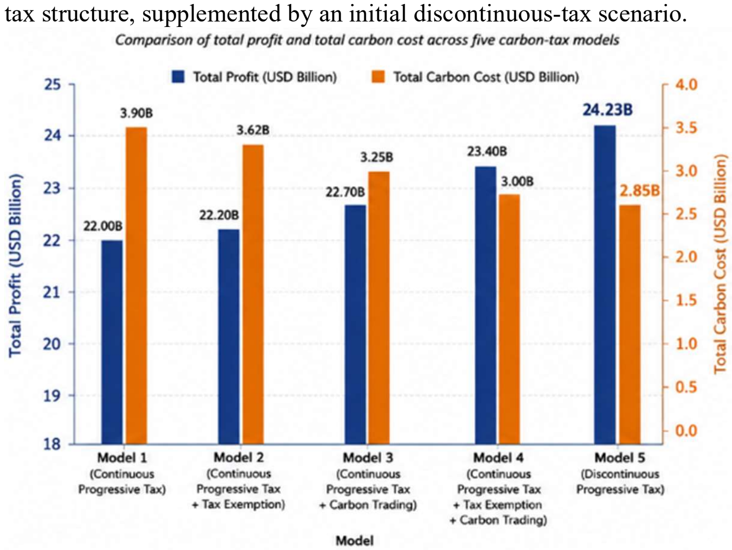

Figure 7. Optimal Solution for Multi-Period Models.

All five models operate under common ESG constraints requiring a progressive reduction in the carbon-emission ratio and an increase in the use of alternative materials. The results demonstrate that the production system can satisfy environmental targets while maintaining positive profitability. Nevertheless, the precise annual carbon-emission ratios, alternative-material quantities, carbon costs, and period-wise profits should be reported separately for the best-performing model among Models 1–5 after verification of all LINGO outputs.

3.2. Sensitivity Analysis

The sensitivity analysis examines the effects of changes in the unit carbon-tax cost on total profitability. All other production, resource, cost, and ESG parameters are held constant. The carbon-tax rate is varied across five scenarios: −20%, −10%, 0%, +10%, and +20%. The results presented in Figure 8 demonstrate a negative relationship between the carbon-tax rate and total profit. A reduction in the carbon-tax rate increases profitability, whereas an increase in the rate reduces profitability because carbon-emission expenditure represents an additional production cost.

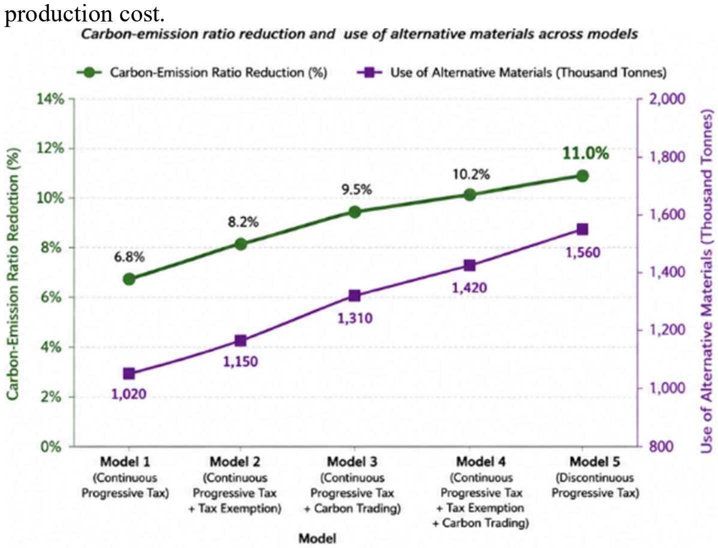

Figure 8. Comparison of Sensitivity Analysis in Multi-period Model.

The magnitude of the profit change differs across Models 1–5 because the models contain different tax, exemption, and trading provisions. Models incorporating tax exemptions or carbon trading can partially reduce the financial exposure associated with changes in carbon-tax costs. In contrast, models without these policy mechanisms are more directly affected by changes in the tax rate. The sensitivity analysis therefore demonstrates that the financial effect of carbon taxation depends not only on the tax rate but also on the design of the carbon-pricing mechanism. The exact sensitivity ranking of Models 1–5 should be presented after verifying the numerical results for every tax-change scenario.

4. DISCUSSION

The results show that the most favourable profitability outcome of the five models kept is the continuous incremental progressive carbon-tax framework with emissions trading (Model 3) [32]. The multi-period optimal profit of model 3 is $22.74486 billion, which is higher than the optimal profit under the basic continuous progressive carbon-tax structure and the other carbon-tax structures that were retained [12]. This outcome illustrates that access to carbon-credit trading can mitigate the financial impact of a carbon tax by enabling firms to buy and sell carbon credits based on their production and emissions situation [3]. The increase in GDP seen in the comparison of Models 1 and 2 suggests that a small increase in profitability can be achieved by implementing a tax exemption [21]. This would imply that a carbon intensive manufacturer is not hit in the short-term with a cost for emitting pollution. Under the assumptions used in this study, however, under the current more profitable model 3, emissions trading offers more economic flexibility than a tax exemption [11]. Model 4 combines the two concepts, tax exemption and emissions trading, into a continuous progressive carbon-tax model. But its reported solution is not profitable as much as Model 3's solution [31]. This finding indicates that the effects of policy instruments are not necessarily cumulative. Final profitability depends on the interplay of the various thresholds, exemption limits, carbon-credit prices, production volumes and emissions control. More policy mechanisms may not necessarily lead to the greatest financial gain [9].

This paper, model 5, examines a discontinuous incremental progressive carbon-tax system [15]. This does not lead to the maximum profit, but it changes how the emissions are distributed across tax-rate bands [2]. This means that the financial efficiency of a carbon tax design is not only dependent on the type of carbon tax (i.e. continuous or discontinuous) but also on the presence of other market mechanisms, like carbon trading [21]. The results of the sensitivity analysis corroborate a negative correlation between the profit and the carbon-tax rate [22]. The total profit decreases as the cost of the carbon-tax rises, since the cost of carbon-emissions becomes a larger part of total input costs [18]. However, the results indicate that this effect can be mitigated in part by the introduction of tax exemptions and emissions-trading systems, as these provide the companies with greater flexibility in complying with the emissions cap [19].

The results show that from a management point of view, the implementation of carbon-pricing policies should be considered as a part of the integrated system of production and cost planning of the cement manufacturer and not as an individual environmental cost [21]. The results show that policy measures like emissions-trading can help to comply with the environment regulations without putting undue strain on the finances of carbon-intensive industries [11]. But the impact of each policy setting relies on the underlying prices of carbon tax, exemption levels, carbon-credit prices, production capacities and emission reduction levels [29]. The present findings have been obtained from a particular set of model assumptions and are to be interpreted in the context of the model optimization selected [28]. The framework could be expanded to include uncertain carbon-credit prices, variable product demand, uncertain energy prices, investment in technology, adoption of renewable-energy technologies, and other potential emission reduction options [18]. The generalizability of the proposed framework may be enhanced by comparative applications in other sectors of the economy that use carbon intensive resources.

5. CONCLUSIONS

This study proposes an integrated ABC–TOC optimization framework for analyzing the impact of carbon taxation, tax exemptions, emissions trading, ESG requirements and resource constraints on cement-manufacturing decisions. The five multi-period carbon pricing models are compared based on the following key evaluation parameters: profitability, carbon-emission costs, reduction in emission intensity and utilization of alternatives materials. The results reveal that model 3 (a continuous incremental progressive carbon tax and emissions trading) is the most lucrative model of the five options studied. It achieves a cumulative profit for all periods of $22.74486 billion. The findings show that emissions trading offers manufacturers more flexibility in the cost and production decisions of carbon-related costs. Tax exemptions also make this system more profitable than the basic carbon-tax system, but have a smaller impact than emissions trading under assumptions used. The sensitivity analysis results show that a higher carbon-tax rate has a negative impact on profitability in the five models. However, policy tools like tax exemption and carbon-credit trading can help mitigate some of the economic consequences of increased carbon prices. The results thus illustrate the need to design carbon-pricing systems taking account of the interplay between the level of taxation, emission allowances, carbon-credit markets, production limitations and environmental goals. The proposed framework is a pragmatic decision support tool for cement producers who wish to optimize production and achieve emissions reduction and ESG goals. It also provides a framework that can be used by policy makers to assess financial and environmental impacts of different carbon pricing methods. The study overall shows that a properly designed carbon-tax and emissions-trading policy can be used to assist in emissions reduction, utilizing resources efficiently, and promoting sustainability of industry in the long-term, while not being overly costly for the cement manufacturer.

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