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An Ecological Cost Accounting Model for Open-Pit Mining: Application to Ultimate Pit Limit Optimization and Slope Angle Optimization Potential Assessment

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Abstract

Ecological disturbance is rarely included as an internal factor in ultimate pit limit design. As a result, conventional methods based on profit maximization are limited in their ability to support green and efficient open-pit mine designing. In this study, an ecological cost accounting model for open-pit mining was developed based on the DPSIR framework. In the proposed model, land occupation and associated ecosystem degradation cost, carbon emission cost, environmental pollution control cost during the mining period, ecological monitoring and maintenance cost, and post-closure reclamation cost were monetized and integrated with economic profit. On this basis, an economic–ecological comprehensive benefit was defined as the difference between economic profit and total ecological cost. This comprehensive benefit was used to support ultimate pit limit scheme selection and the assessment of slope angle optimization potential. A set of candidate ultimate pit limit schemes was generated for a large open-pit iron mine under different combinations of zonal slope angles and open-pit scales. The ecological costs of the candidate schemes were mainly between USD 1160 million and USD 1350 million. In terms of cost composition, land occupation and associated ecosystem degradation cost accounted for approximately 67.3% of the total ecological cost. After ecological cost was included, the peak of the economic–ecological comprehensive benefit shifted toward a smaller open-pit scale, indicating that profit maximization alone may lead to excessive pit expansion. Zonal sensitivity analysis showed that the strongest responses on slope angle optimization potential were found in Zones 4# and 3#. For each 1° increase in slope angle, average increases of approximately USD 41.38 million and USD 35.32 million in pit profit were obtained in Zones 4# and 3#, respectively.

Keywords: open-pit mining; ultimate pit limit; ecological cost; DPSIR framework; slope angle

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1. Introduction

Open-pit mining has been widely used for the extraction of coal, metallic minerals, and some non-metallic minerals because of its high production capacity, high level of mechanization, and favorable resource recovery conditions [1,2]. However, open-pit mining also causes strong disturbance to surface ecosystems [3]. During the development and operation of an open-pit mine, a series of engineering activities is usually involved, including mining infrastructure construction, overburden stripping, excavation and loading, haulage, waste rock dumping, mineral processing, tailings disposal, and mine closure and reclamation, which are commonly associated with many ecological and environmental problems. These problems include land occupation, landform change, loss of ecosystem service functions, increased energy consumption, carbon emissions, dust generation, wastewater discharge, and solid waste generation [4–6].

Extensive research has been conducted worldwide on the investigation, monitoring, and assessment of ecological and environmental issues in open-pit mining [7,8]. With the development of remote sensing, geographic information technologies, and multi-source data fusion methods, ecological and environmental surveys in open-pit mining areas have gradually changed from local field investigation to large-scale and long-term dynamic monitoring [9]. Previous studies have been mainly focused on three aspects [10–16]. First, surface disturbance and changes in ecological and environmental quality caused by open-pit mining have been identified using remote-sensing images from different periods. Second, vegetation damage, land damage, and ecological restoration processes have been assessed quantitatively. Third, the effects of open-pit mining on ecosystem service functions have been analyzed from the perspective of ecosystem services, including carbon sequestration, soil conservation, and water regulation.

On this basis, recent studies have increasingly focused on the quantitative assessment of ecological impacts in open-pit mining and their surrounding areas. These studies have mainly been conducted from the perspectives of remote-sensing ecological indices, land-use change, ecosystem service value, landscape ecological risk, and cumulative ecological effects. A pixel-based time series model of ecosystem service value was proposed by Li et al. [17] to quantify the cumulative ecological effects in mining areas. By assessing ecological impacts from spatial, temporal, and value dimensions, this model was used to reveal the spatial heterogeneity and temporal changes of ecological losses caused by mining, rather than only providing a static interpretation of land use. Long-term remote-sensing data were further used by Yang et al. [18] to assess the cumulative ecological effects caused by mining disturbance. This approach improved the efficiency of large-scale and continuous monitoring. In arid and semi-arid mining regions, Wu et al. [19] assessed the effects of open-pit mining on ecosystem service value using time-series remote-sensing images and GEE. The results showed that ecological impact assessment has gradually changed from surface disturbance mapping to the assessment of ecosystem service functions. Liu et al. [20] quantified the impact of coal mining on the ecological environment of Gobi open-pit mining by combining improved remote-sensing ecological indicators with attribution analysis, which is particularly useful for distinguishing ecological degradation caused by mining from background environmental variation. In addition, studies based on ecosystem services have been used to assess the effects of mining activities on water yield, net primary productivity, soil conservation, habitat quality, and the relationships among ecosystem services [21,22]. Landscape ecological risk assessment and ecological network analysis have also been used to reveal spatial fragmentation and changes in ecological security patterns caused by open-pit mining [23]. At broader scales, Xiang et al. [24] demonstrated that surface mining can lead to multiple ecosystem service losses, while Shi et al. [25] introduced gross ecosystem product accounting to evaluate ecosystem service values in large-scale

open-pit coal mining areas. These studies have improved the quantitative understanding of ecological disturbance caused by mining. However, most of them are still focused on ecological monitoring, spatial and temporal assessment, or regional ecosystem service valuation. Their outputs are usually represented by ecological indices, ecosystem service values, risk levels, or spatial patterns of ecological degradation. Although these results are useful for identifying the location, extent, and evolution of ecological impacts, they are not directly linked to the engineering characteristics of candidate ultimate pit limit schemes, such as pit geometry. Therefore, ecological information derived from these studies cannot be directly used for ultimate pit limit scheme selection unless it is further converted into ecological cost indicators for each scheme.

The monetary valuation of ecosystem services provides an important basis for converting ecological impacts into comparable monetary values. In previous studies, a variety of economic valuation methods have been used, including market-based methods, revealed preference methods, stated preference methods, value transfer methods, and other nonmarket valuation methods [26]. In studies on ecosystem service value, the equivalent factor method has also been widely applied, especially in assessments based on land-use and regional-scale analysis. However, it has been shown in previous meta-analyses that ecosystem service values may vary greatly among different ecosystem types, service categories, valuation methods, and socioeconomic contexts [27].

In addition to quantitative assessment methods, a conceptual framework is needed to organize the different ecological impacts caused by open-pit mining activities. The Driver–Pressure–State–Impact–Response (DPSIR) framework has been widely used to describe the relationships between human activities and environmental changes by linking socioeconomic driving forces, environmental pressures, changes in ecological state, impacts on ecosystem functions, and management responses within a cause–effect chain. Döhren and Haase [28] combined the DPSIR framework with the ecosystem service cascade approach to identify the causal pathways through which post mining landscapes and ecosystem service potential are affected by coal and lignite mining, especially surface and opencast mining. Lin et al. [29] combined the DPSIR model with a Fuzzy-DEMATEL approach to identify influencing factors in green mining construction. These studies indicate that DPSIR can be used to organize resource, environmental, ecological, and management factors in mining. However, in existing mining studies, the DPSIR framework has mainly been used for qualitative diagnosis, indicator organization, or factor identification. Its potential for guiding the classification of monetized ecological cost items and supporting the evaluation of ultimate pit limit schemes has not been sufficiently explored.

Substantial progress has been made in mining-related ecological and environmental studies, including life-cycle assessment, ecosystem service valuation, carbon emission accounting, and pollution control analysis. Ecological cost has also been introduced into ultimate pit limit optimization in previous studies [30,31]. However, these studies were mainly focused on open-pit coal mines. Reference [30] considered environmental problems in ultimate pit optimization. Reference [31] further integrated ecological cost, slope safety, and economic benefit in the case of the open-pit coal mine. These studies provided an important basis for including ecological and environmental factors in open-pit mine design. However, several issues still need to be addressed. First, ecological cost items have not been organized through a complete cause and effect framework that links mining drivers, environmental pressures, changes in environmental state, ecological impacts, and management responses. Second, a unified ecological cost accounting structure remains insufficiently developed. Such a structure should consider land occupation and associated ecosystem degradation, carbon emissions, pollution control, ecological monitoring and maintenance, and post-closure reclamation at the same time. Third, most existing appli-

cations were based on coal mines. In contrast, large open-pit iron mines have different orebody geometry, mining scale, waste rock stripping characteristics, land disturbance patterns, and tailings storage demand. Fourth, the responses of ecological cost and economic and ecological comprehensive benefit to coupled changes in zonal slope angles and open-pit scale have not been fully quantified. Fifth, the effects of carbon trading price fluctuations on ecological cost accounting results have not been sufficiently assessed. Therefore, an ecological cost accounting model was proposed in this study to evaluate ultimate pit limit schemes in a large, open-pit iron mine. Compared with References [30,31], the contributions of this study are reflected in five aspects: (i) A DPSIR-based ecological cost identification framework was introduced. This framework provided a clearer logical basis for converting ecological disturbance processes into monetized ecological cost items. (ii) The ecological cost accounting structure was refined into five explicit categories. These categories included land occupation and associated ecosystem degradation cost, carbon emission cost, environmental pollution control cost during the mining period, ecological monitoring and maintenance cost, and post-closure reclamation cost. (iii) The model was applied to a large, open-pit iron mine. Compared with previous coal mine cases, the iron mine case involved more slope zones, more complex orebody geometry, and stronger spatial differences in ore and waste rock distribution. Therefore, this application extends ecological cost accounting to a metallic open-pit mine case with more complex engineering and ecological characteristics. (iv) The optimization potential of different slope angle zones was assessed from the perspective of economic and ecological comprehensive benefit. This made it possible to identify candidate zones for further geotechnical assessment and slope optimization before detailed slope stability verification. In addition, a carbon trading price sensitivity analysis was conducted to assess the influence of carbon price fluctuations on ecological cost accounting results. These contributions provide an operational basis for including ecological costs in the evaluation of ultimate pit limit schemes at the early stage of open-pit mine planning.

2. Materials and Methods

2.1. DPSIR-Based Identification of Ecological Cost Categories for Open-Pit Mining

The ecological impacts of open-pit mining on mining areas and surrounding areas are characterized by multiple disturbance sources, multiple environmental media, and cumulative effects. Based on the engineering processes of open-pit mining and previous studies on mining induced ecological impacts, the major ecological disturbances caused by open-pit mining can be classified into four categories. The first category is land and ecosystem degradation, which mainly results from pit excavation, waste dump construction, tailings ponds, and industrial land occupation. These activities lead to land occupation, geomorphological reshaping, soil structure damage, and vegetation loss. As a result, the continuity and stability of the original ecosystem are reduced. The second category is carbon emissions, which are mainly associated with fuel consumption, electricity consumption, explosive use, and the reduction in carbon sequestration capacity caused by land disturbance. The third category is environmental pollution. This category includes the effects of dust, wastewater, exhaust gas, solid waste, and potential heavy metal contamination on soil, water, and air during mining, mineral processing, and waste discharge. The fourth category is secondary disasters and soil erosion, which are closely related to high and steep slopes, loose waste rock dumps, and tailings ponds. Under rainfall, weathering, and continuous mining disturbance, these engineering structures may cause landslides, collapses, debris flows, and soil erosion.

These ecological impacts are not generated independently. They are formed through a continuous process that includes resource development demand, engineering disturbance,

changes in environmental state, ecological impacts, and management responses. To identify the sources, transmission pathways, and corresponding ecological cost items of impacts caused by open-pit mining, the DPSIR framework was introduced in this study. The DPSIR was not used as a direct quantitative evaluation model, but as a conceptual tool for ecological impact identification and ecological cost classification. Based on the process characteristics of open-pit mining, a DPSIR-based identification framework for ecological cost accounting was established, as shown in Figure 1.

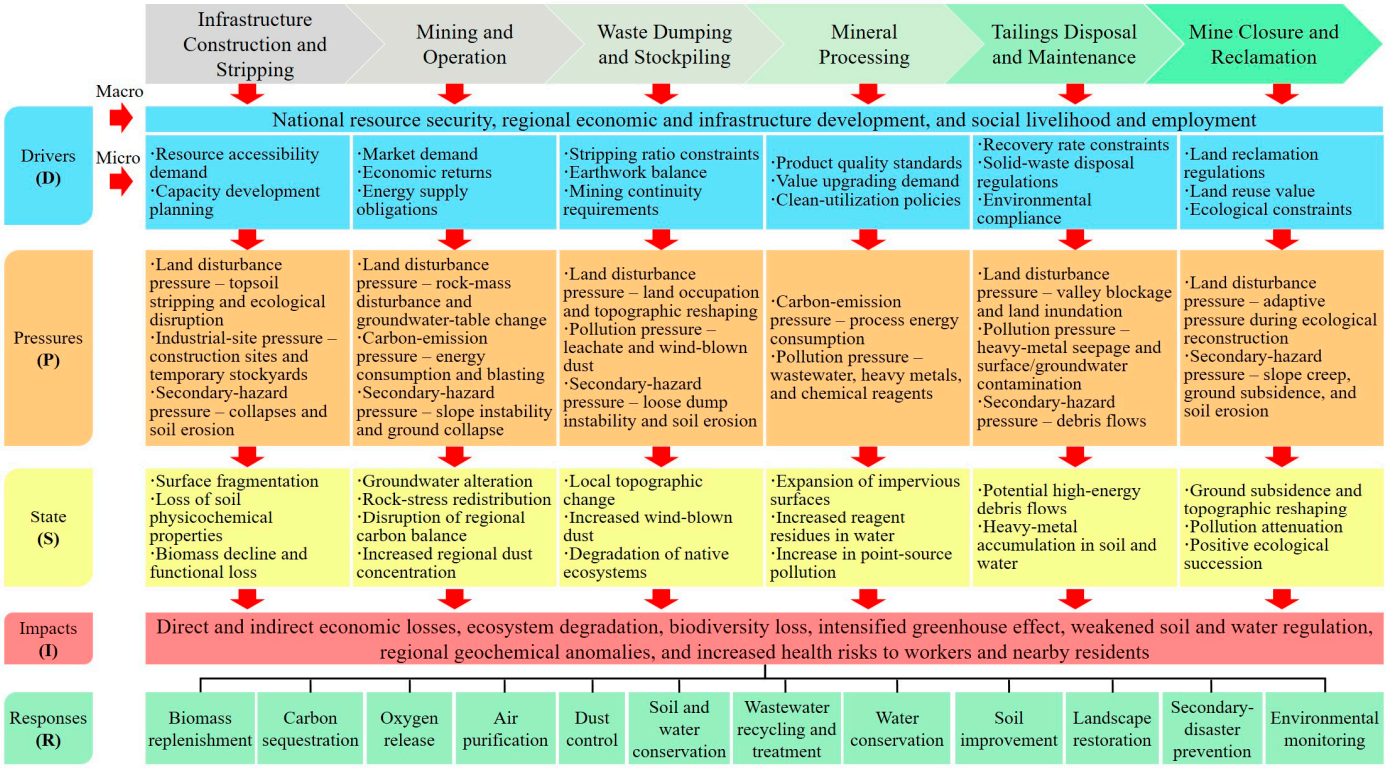


Figure 1. DPSIR-based framework for identifying ecological cost categories in open-pit mining.

In the driver layer, open-pit mining is driven by mineral resource demand, economic benefits, production scale, market conditions, and green mine construction requirements. In the pressure layer, pit excavation, topsoil stripping, waste rock dumping, tailings discharge, energy consumption, and pollutant emissions place direct pressures on the ecological environment. In the state layer, these pressures further change land use, geomorphology, soil structure, vegetation cover, groundwater conditions, air quality, and landscape connectivity in the mining area. In the impact layer, changes in environmental state are reflected in the degradation of ecosystem services, increased carbon emissions, environmental pollution damage, habitat fragmentation, and increased geological hazard risks. In the response layer, mining enterprises and regulatory authorities need to implement land reclamation, vegetation restoration, soil and water conservation, pollution control, carbon reduction, disaster prevention, and environmental monitoring measures to mitigate ecological damage and maintain ecological security in mining areas. Although the DPSIR framework was used as a conceptual tool rather than as a direct quantitative model in this study, a necessary causal structure for ecological cost identification was provided by this framework. Its added value was reflected in the systematic connection between pressures caused by open-pit mining, changes in environmental state, ecological impacts, and management responses. This role was different from a simple listing of ecological impact types. Through this cause–effect chain, ecological disturbances were systematically traced to corresponding cost-bearing processes, including land occupation, ecosystem service degradation, carbon

emissions, pollution control, ecological monitoring, and post-closure reclamation. Accordingly, the ecological impacts identified through the DPSIR framework were further converted into monetized ecological cost items, including land occupation and associated ecosystem degradation cost, carbon emission cost, environmental pollution control cost during the mining period, ecological monitoring and maintenance cost, and post-closure reclamation cost. This classification covers the major ecological and environmental impacts caused by open-pit mining and provides a basis for the unified accounting of ecological costs and economic–ecological comprehensive benefit analysis under different ultimate pit limit schemes.

2.2. Ecological Cost Accounting Model for Open-Pit Mining

Based on the DPSIR-based identification of ecological impact categories, an ecological cost accounting model for open-pit mining was established in this section. The model was developed by extending and supplementing our previous studies [30,31]. To improve the readability of the ecological cost accounting model, the main abbreviations and symbols used in the formula system are summarized in Table 1.

Table 1. Main abbreviations and symbols used in the ecological cost accounting model.

Abbreviation & Symbol	Meaning
$E_{\text{total}}(V_i, T_i)$	Total ecological cost of open-pit mining
$E_{\text{D}}(V_i, T_i)$	Land occupation and associated ecosystem degradation cost
$E_{\text{C}}(V_i, T_i)$	Carbon emission cost
$E_{\text{T}}(V_i, T_i)$	Environmental pollution control cost during the mining period
$E_{\text{M}}(V_i, T_i)$	Ecological monitoring and maintenance cost
$E_{\text{R}}(V_i, T_i)$	Post-closure reclamation cost
$v_{\text{yield}}(V_i, T_i)$	Biomass production service value of the pre-mining ecosystem
$v_{\text{oxy}}(V_i, T_i)$	Oxygen release service value of the pre-mining ecosystem
$v_{\text{air}}(V_i, T_i)$	Air purification service value of the pre-mining ecosystem
$v_{\text{soil}}(V_i, T_i)$	Soil conservation service value of the pre-mining ecosystem
$v_{\text{wat}}(V_i, T_i)$	Water conservation service value of the pre-mining ecosystem
$v_{\text{neu}}(V_i, T_i)$	Nutrient cycling service value of the pre-mining ecosystem
$v_{\text{sce}}(V_i, T_i)$	Landscape and recreation service value of the pre-mining ecosystem
C_{S}	Total carbon emissions of open-pit mining
C_{D}	Direct carbon emissions of open-pit mining
C_{I}	Indirect carbon emissions of open-pit mining
C_{DE}	Carbon emissions associated with electricity consumption
C_{DO}	Carbon emissions generated by fossil fuel consumption
C_{DB}	Carbon emissions generated by explosive detonation during blasting
C_{DM}	Carbon emission generated during ore mineral processing
C_{IF}	Loss of carbon sequestration caused by land disturbance in pit area
C_{IR}	Loss of carbon sequestration caused by land disturbance in waste dump
C_{IT}	Loss of carbon sequestration caused by land disturbance in tailings pond
C_{IS}	Embodied carbon emissions from the production and transportation of raw materials used for the construction of auxiliary facilities
C_{IE}	Difference between carbon sequestration during the reclamation period and carbon sequestration by the pre-mining ecosystem
$v_{\text{dus}}(V_i, T_i)$	Dust pollution control cost
$v_{\text{sew}}(V_i, T_i)$	Wastewater treatment cost
$v_{\text{mon}}(V_i, T_i)$	Investment cost of ecological monitoring equipment and systems
$v_{\text{ope}}(V_i, T_i)$	Routine ecological monitoring and maintenance cost
$v_{\text{main-dum}}(V_i, T_i)$	Waste dump maintenance cost
$v_{\text{main-pon}}(V_i, T_i)$	Tailings pond maintenance cost
$v_{\text{dis}}(V_i, T_i)$	Cost of secondary disaster prevention and soil and water conservation

For any pit limit V_i, there is a corresponding mine life T_i. The ecological cost can be calculated using Equation (1):

$$E_{\text{total}}(V_i, T_i) = E_{\text{D}}(V_i, T_i) + E_{\text{C}}(V_i, T_i) + E_{\text{T}}(V_i, T_i) + E_{\text{M}}(V_i, T_i) + E_{\text{R}}(V_i, T_i) \quad (1)$$

where $E_{\text{D}}(V_i, T_i)$ is the land occupation and associated ecosystem degradation cost, USD, $E_{\text{C}}(V_i, T_i)$ is the carbon emission cost, USD, $E_{\text{T}}(V_i, T_i)$ is the environmental pollution control cost during the mining period, USD, $E_{\text{M}}(V_i, T_i)$ is the ecological monitoring and maintenance cost, USD, and $E_{\text{R}}(V_i, T_i)$ is the post-closure reclamation cost, USD.

Specifically, the land occupation and associated ecosystem degradation cost $E_{\text{D}}(V_i, T_i)$ can be calculated using Equation (2):

$$\begin{aligned} E_{\text{D}}(V_i, T_i) = v_{\text{yield}}(V_i, T_i) + v_{\text{oxy}}(V_i, T_i) + v_{\text{air}}(V_i, T_i) + v_{\text{soil}}(V_i, T_i) \\ + v_{\text{wat}}(V_i, T_i) + v_{\text{neu}}(V_i, T_i) + v_{\text{sce}}(V_i, T_i) \end{aligned} \quad (2)$$

where $v_{\text{yield}}(V_i, T_i)$ is the biomass production service value of the pre-mining ecosystem, USD, $v_{\text{oxy}}(V_i, T_i)$ is the oxygen release service value of the pre-mining ecosystem, USD, $v_{\text{air}}(V_i, T_i)$ is the air purification service value of the pre-mining ecosystem, USD, $v_{\text{soil}}(V_i, T_i)$ is the soil conservation service value of the pre-mining ecosystem, USD, $v_{\text{wat}}(V_i, T_i)$ is the water conservation service value of the pre-mining ecosystem, USD, $v_{\text{neu}}(V_i, T_i)$ is the nutrient cycling service value of the pre-mining ecosystem, USD, and $v_{\text{sce}}(V_i, T_i)$ is the landscape and recreation service value of the pre-mining ecosystem, USD.

The biomass production service value was treated as a one-time stock value loss. The biomass production service value of the pre-mining ecosystem can be calculated using Equation (3):

$$v_{\text{yield}}(V_i, T_i) = \Delta v_{\text{yield}} A_{\text{total}} \quad (3)$$

where Δv_{yield} is the biomass production service value per unit land area, USD/hm^2, and A_{total} is the total land acquisition area, calculated according to the land acquisition area, hm^2.

The oxygen release service value of the pre-mining ecosystem can be calculated using Equation (4):

$$v_{\text{oxy}}(V_i, T_i) = \sum_{n=1}^{T_i} y_{\text{npp}} f_{\text{O}_2} c_{\text{O}_2} [A_{\text{M}}(V_i, t) + A_{\text{D}}(V_i, t) + A_{\text{T}}(V_i, t) + A_{\text{B}}(V_i, t)] \quad (4)$$

where y_{npp} is the net primary productivity per unit land area, t/(hm^2·a), f_{O_2} is the oxygen release coefficient, namely the amount of oxygen released per unit net primary production, taken as 1.20, c_{O_2} is the oxygen acquisition cost, USD/t, $A_{\text{M}}(V_i, t)$ is the cumulative disturbed surface area of the open-pit area at the end of year t, hm^2, which can be calculated from the surface boundary line of the pit limit at the end of year t, $A_{\text{D}}(V_i, t)$ is the cumulative disturbed surface area of the waste dump at the end of year t, hm^2, $A_{\text{T}}(V_i, t)$ is the disturbed surface area of the tailings pond at the end of year t, hm^2, and $A_{\text{B}}(V_i, t)$ is the cumulative occupied area of auxiliary facilities and equipment at the end of year t, hm^2.

The cumulative disturbed surface area of the waste dump at the end of year t can be calculated using Equation (5):

$$A_{\text{D}}(V_i, t) = \frac{W(V_i, t) k_w}{\gamma_w H_{\text{D}}} f_{\text{D}} \quad (5)$$

where $W(V_i, t)$ is the cumulative amount of waste rock stripped at the end of year t, 10^4 t, γ_w is the average bulk density of waste rock, t/m^3, k_w is the bulking coefficient of waste

rock, taken as 1.10–1.35, H_D is the average dumping height of the waste dump, m, and f_D is the shape coefficient of the waste dump.

The disturbed surface area of the tailings pond at the end of year t can be calculated using Equation (6):

$$A_T(V_i, t) = \frac{Q(V_i, t)\left(1 - \frac{g_0}{g_P} r_P\right)}{\gamma_T H_T} f_T \quad (6)$$

where $Q(V_i, t)$ is the cumulative tonnage of ore processed at the end of year t, 10^4 t, g_0 is the average grade of the run-of-mine ore, %, g_P is the average grade of the concentrate, %, r_P is the mineral processing recovery rate, %, γ_T is the average bulk density of deposited tailings, t/m^3, H_T is the average height of the tailings pond, m, and f_T is the shape coefficient of the tailings storage facility.

The air purification service value of the pre-mining ecosystem can be calculated using Equation (7):

$$v_{air}(V_i, T_i) = f_C \sum_{n=1}^{T_i} \left(a_{SO_2} c_{SO_2} + a_{dus} c_{dus}\right)[A_M(V_i, t) + A_D(V_i, t) + A_T(V_i, t) + A_B(V_i, t)] \quad (7)$$

where a_{SO_2} is the annual average SO_2 absorption capacity of the pre-mining ecosystem, t/(hm^2·a), c_{SO_2} is the unit SO_2 treatment cost, USD/t SO_2, a_{dus} is the annual average dust retention capacity of the damaged land ecosystem, t/(hm^2·a), c_{dus} is the unit dust removal cost, USD/t, and f_C is the annual ecological function coefficient of the regional ecosystem.

The soil conservation service value of the pre-mining ecosystem can be calculated using Equation (8):

$$v_{soil}(V_i, T_i) = y_s \sum_{n=1}^{T_i} \frac{s_r}{10000 \gamma_s h_s}[A_M(V_i, t) + A_D(V_i, t) + A_T(V_i, t) + A_B(V_i, t)] \quad (8)$$

where s_r is the annual average soil conservation capacity of the pre-mining ecosystem, t/(hm^2·a), γ_s is the average soil bulk density, t/m^3, h_s is the average soil thickness, m, and y_s is the unit-area economic value of conserved soil when it is valued as productive land, USD/hm^2.

The water conservation service value of the pre-mining ecosystem can be calculated using Equation (9):

$$v_{wat}(V_i, T_i) = 10 p_r k_r f_p c_{wat} \sum_{n=1}^{T_i} [A_M(V_i, t) + A_D(V_i, t) + A_T(V_i, t) + A_B(V_i, t)] \quad (9)$$

where p_r is the regional annual average precipitation, mm/a, k_r is the proportion of runoff-generating rainfall to total precipitation in the region, %, f_p is the runoff reduction coefficient of the pre-mining ecosystem relative to bare land, and c_{wat} is the unit price of water resources, USD/m^3.

The nutrient cycling service value of the pre-mining ecosystem can be calculated using Equation (10):

$$v_{neu}(V_i, T_i) = y_{npp}\left(k_N p_N + k_P f_{P_2O_5} p_P + k_K p_K\right) \sum_{n=1}^{T_i} [A_M(V_i, t) + A_D(V_i, t) + A_T(V_i, t) + A_B(V_i, t)] \quad (10)$$

where k_N, k_P, k_K are the proportions of N, P, and K elements in net primary production, respectively, %, $f_{P_2O_5}$ is the conversion coefficient from P to P_2O_5, taken as 2.2903, and p_N, p_P, p_K are the prices of nitrogen fertilizer, phosphate fertilizer, and potassium fertilizer, respectively, USD/t.

The landscape and recreation service value of the pre-mining ecosystem can be calculated using Equation (11):

$$v_{\mathrm{sce}}(V_i, T_i) = c_{\mathrm{sce}} f_{\mathrm{cul}} \sum_{n=1}^{T_i} [A_{\mathrm{M}}(V_i, t) + A_{\mathrm{D}}(V_i, t) + A_{\mathrm{T}}(V_i, t) + A_{\mathrm{B}}(V_i, t)] \quad (11)$$

where c_{sce} is the average annual willingness-to-pay value for preserving the pre-mining natural landscape, USD/(hm^2·a), and f_{cul} is the equivalent factor per unit area of the mining ecosystem in providing aesthetic and recreation functions.

The carbon emission cost was calculated by multiplying the generated carbon emissions by the carbon trading price. The carbon emission cost can be calculated using Equation (12):

$$E_{\mathrm{C}}(V_i, T_i) = c_{\mathrm{car}} C_{\mathrm{S}} \quad (12)$$

where c_{car} is the carbon trading price, USD/t CO_2, and C_{S} is the total carbon emissions of open-pit mining, t CO_2.

The carbon emissions accounting model for open-pit mining is as follows:

$$C_{\mathrm{S}} = C_{\mathrm{D}} + C_{\mathrm{I}} \quad (13)$$

where C_{D} is the direct carbon emissions of open-pit mining, t CO_2, and C_{I} is the indirect carbon emissions of open-pit mining, t CO_2.

The direct carbon emission of open-pit mining can be calculated using Equation (14):

$$C_{\mathrm{D}} = C_{\mathrm{DE}} + C_{\mathrm{DO}} + C_{\mathrm{DB}} + C_{\mathrm{DM}} \quad (14)$$

where C_{DE} is the carbon emissions associated with electricity consumption, t CO_2, C_{DO} is the carbon emissions generated by fossil fuel consumption, t CO_2, C_{DB} is the carbon emissions generated by explosive detonation during blasting, t CO_2, and C_{DM} is the carbon emissions generated during ore mineral processing, t CO_2.

The carbon emissions generated by electricity consumption in open-pit mining can be calculated using Equation (15):

$$C_{\mathrm{DE}} = [Q(e_{\mathrm{W1}} + e_{\mathrm{W2}}) + T_i e_{\mathrm{W3}}]\eta_{\mathrm{e}} \quad (15)$$

where Q is the total tonnage of mined ore and stripped waste rock, t, e_{W1} is the average electricity consumption for mining or stripping, including drilling and blasting, per unit ore or rock, kW·h/t, e_{W2} is the average electricity consumption for handling, including loading and haulage, per unit mined ore or stripped rock, kW·h/t, e_{W3} is the annual average total electricity consumption of mine auxiliary facilities, office areas, and auxiliary equipment, kW·h/a, and η_e is the carbon emission factor of electricity, t CO_2/kW·h.

The carbon emissions generated by fossil fuel consumption can be calculated using Equation (16):

$$C_{\mathrm{DO}} = Q[(d_{\mathrm{W1}} + d_{\mathrm{W3}})\eta_{\mathrm{d1}} + (d_{\mathrm{W2}} + d_{\mathrm{W4}})\eta_{\mathrm{d2}}] \quad (16)$$

where d_{W1} is the average gasoline consumption for mining or stripping, including drilling and blasting, per unit mined ore or stripped rock, t/t, d_{W3} is the average diesel consumption for mining or stripping, including drilling and blasting, per unit mined ore or stripped rock, t/t, d_{W2} is the average gasoline consumption for handling, including loading and haulage, per unit mined ore or stripped rock, t/t, d_{W4} is the average diesel consumption for handling, including loading and haulage, per unit mined ore or stripped rock, t/t, η_{d1} is the gasoline carbon emission factor, t CO_2/t, and η_{d2} is the diesel carbon emission factor, t CO_2/t.

The carbon emissions generated by explosive detonation during blasting can be calculated using Equation (17):

$$C_{\mathrm{DB}} = Q\frac{b_{\mathrm{w}}\eta_{\mathrm{b}}}{\gamma} \tag{17}$$

where b_{w} is the unit explosive consumption per unit volume of blasted ore and rock, t/m^3, η_b is the carbon emission factor of detonated explosives, t CO_2/t, and γ is the average bulk density of ore and rock, t/m^3.

Assuming that the carbon emissions generated in the mineral processing process are all attributable to electricity consumption, the carbon emissions from ore mineral processing can be calculated using Equation (18):

$$C_{\mathrm{DM}} = Q_1 m_{\mathrm{w}} \eta_{\mathrm{e}} \tag{18}$$

where Q_1 is the tonnage of run-of-mine ore fed into ore mineral processing, t, and m_{w} is the unit electricity consumption of the processing plant per tonne of run-of-mine ore processed, kW·h/t.

The indirect carbon emissions of open-pit mining can be calculated using Equation (19):

$$C_{\mathrm{I}} = C_{\mathrm{IF}} + C_{\mathrm{IR}} + C_{\mathrm{IT}} + C_{\mathrm{IS}} + C_{\mathrm{IE}} \tag{19}$$

where C_{IF} is the loss of carbon sequestration caused by land disturbance in pit area, t CO_2, C_{IR} is the loss of carbon sequestration caused by land disturbance in waste dump, t CO_2, C_{IT} is the loss of carbon sequestration caused by land disturbance in tailings pond, t CO_2, C_{IS} is the embodied carbon emissions from the production and transportation of raw materials used for the construction of auxiliary facilities, t CO_2, and C_{IE} is the difference between carbon sequestration during the reclamation period and carbon sequestration by the pre-mining ecosystem, t CO_2.

The loss of carbon sequestration caused by land disturbance in the pit area can be calculated using Equation (20):

$$C_{\mathrm{IF}} = \sum_{i=1}^{n} A_{\mathrm{M}}(V_i, t)\left(p_t y_{\mathrm{npp}} f_{CO_2} + q_t h_{\mathrm{sg}} \gamma_{\mathrm{sg}} r_{\mathrm{so}} r_{\mathrm{oc}} \zeta\right) \tag{20}$$

where p_t is the proportion of forestland area of the open-pit area in year t, %, q_t is the proportion of grassland area of the pit area in year t, %, f_{CO_2} is the forestland CO_2 fixation coefficient, h_{sg} is the average soil thickness of disturbed grassland, m, γ_{sg} is the average soil bulk density of disturbed grassland, t/m^3, r_{so} is the soil organic matter content, %, r_{oc} is the carbon content proportion in soil organic matter, %, and ζ is the conversion coefficient from carbon to CO_2 conversion coefficient, taken as 3.6667.

The loss of carbon sequestration caused by land disturbance in waste dump can be calculated using Equation (21):

$$C_{\mathrm{IR}} = \sum_{i=1}^{n} \frac{R_t k_{\mathrm{w}}}{H_{\mathrm{D}} \gamma_{\mathrm{w}}} f_{\mathrm{D}} p_t y_{\mathrm{npp}} f_{CO_2} \tag{21}$$

where R_t is the cumulative amount of waste rock deposited in waste dump at the end of year t, t.

The loss of carbon sequestration caused by land disturbance in tailings pond can be calculated using Equation (22):

$$C_{\mathrm{IT}} = \frac{Q_1}{\gamma_{\mathrm{T}} H_{\mathrm{T}}}\left(1 - \frac{g_{\mathrm{o}}}{g_{\mathrm{p}}} r_{\mathrm{p}}\right) f_{\mathrm{T}}\left(p_t y_{\mathrm{npp}} f_{CO_2} + q_t h_{\mathrm{s}} \gamma_{\mathrm{s}} r_{\mathrm{so}} r_{\mathrm{oc}} \zeta\right) T_i \tag{22}$$

where γ_T is the average bulk density of deposited tailings, t/m^3, H_T is the average depth of the tailings pond, m, and f_T is the shape coefficient of the tailings pond.

The embodied carbon emissions from the production and transportation of raw materials used for the construction of auxiliary facilities can be calculated using Equation (23):

$$C_{IS} = V_c cem_{CO_2} + V_b b_{CO_2} + V_c t_{w1} \eta_{d2} + V_b t_{w2} \eta_{d2} \quad (23)$$

where V_c is the total volume of concrete used for auxiliary facility construction in the open-pit mine, m^3, cem_{CO_2} is the embodied carbon emissions factor of concrete, t CO_2/m^3, V_b is the total mass of steel reinforcement used for auxiliary facility construction, m^3, b_{CO_2} is the embodied carbon emission factor of steel reinforcement, t CO_2/m^3, t_{w1} is the diesel consumption for transporting a unit volume of concrete t/m^3, and t_{w2} is the diesel consumption for transporting a unit volume of steel reinforcement, t/m^3.

The difference between carbon sequestration during the reclamation period and carbon sequestration by the pre-mining ecosystem can be calculated using Equation (24):

$$C_{IE} = A_R \sum_{n=1}^{i} p_t (y_{npp} - y_{npp i}) f_{CO_2} + q_t (h_s \gamma_s r_{so} r_{oc} - h_{si} \gamma_{si} r_{soi} r_{oci}) \zeta \quad (24)$$

where A_R is the reclamation area, hm^2, $y_{npp i}$ is the net primary productivity of forestland at the end of reclamation year i (t/hm^2·a), h_{si} is the average soil thickness of grassland at the end of reclamation year i, m, γ_{si} is the average soil bulk density of grassland at the end of reclamation year i, t/m^3, r_{soi} is the soil organic matter content at the end of reclamation year i, %, and r_{oci} is the carbon content proportion in soil organic matter at the end of reclamation year i, %.

The environmental pollution control cost during the mining period mainly included the direct costs of treating exhaust gas, dust, and wastewater in the mining area, such as pit dust suppression and wastewater treatment.

The environmental pollution control cost during the mining period can be calculated using Equation (25):

$$E_T(V_i, T_i) = v_{dus}(V_i, T_i) + v_{sew}(V_i, T_i) \quad (25)$$

where $v_{dus}(V_i, T_i)$ is the dust pollution control cost, USD, and $v_{sew}(V_i, T_i)$ is the wastewater treatment cost, USD.

The dust pollution control cost can be calculated using Equation (26):

$$v_{dus}(V_i, T_i) = (Q_i + W_i) k_{bls} c_{dus} \quad (26)$$

where Q_i is the ore tonnage mined, t, W_i is the rock tonnage stripped, t, and k_{bls} is the dust generation coefficient per unit mass of mined ore or stripped rock, t/t.

For the wastewater treatment cost, mine wastewater was assumed to originate mainly from three sources, including accumulated water in the pit and groundwater inflow, mineral processing plant wastewater, and domestic wastewater generated in the mining area.

The wastewater treatment cost can be calculated using Equation (27):

$$v_{sew}(V_i, T_i) = 10,000 c_{pitw} \sum_{n=1}^{T_i} (k_{gw} + k_{rw}) A_M(V_i, t) + c_{pro} Q_i \omega_{ore} + \omega_{per} r_n c_{dom} T_i \quad (27)$$

where c_{pitw} is the unit treatment cost of pit wastewater, USD/m^3, k_{gw} is the groundwater inflow coefficient,k_{rw} is the regional annual average rainfall catchment coefficient (which can be obtained by multiplying the local annual precipitation by the surface runoff coefficient), c_{pro} is the unit cost of advanced treatment for mineral processing wastewater,

including heavy metal removal and reagent degradation, USD/m^3, ω_{ore} is the wastewater generation coefficient per unit run-of-mine ore processed during mineral processing, m^3/t, ω_{per} is the annual domestic wastewater discharge coefficient per employee in the mining area, t/(person·a), and c_{dom} is the unit treatment cost of domestic wastewater, USD/m^3; r_n is the number of employees.

The ecological monitoring and maintenance cost can be divided into one-time investment costs and costs related to routine management during the mine life. The routine management costs mainly included ecological monitoring and maintenance, waste dump and tailings pond maintenance, secondary disaster prevention, and soil and water conservation, which can be estimated according to the mine life.

The ecological monitoring and maintenance cost can be calculated using Equation (28):

$$E_M(V_i, T_i) = v_{mon}(V_i, T_i) + v_{ope}(V_i, T_i) + v_{main-dum}(V_i, T_i) + v_{main-pon}(V_i, T_i) + v_{dis}(V_i, T_i) \quad (28)$$

where $v_{mon}(V_i, T_i)$ is the investment cost of ecological monitoring equipment and systems, USD, $v_{ope}(V_i, T_i)$ is the routine ecological monitoring and maintenance cost, USD, $v_{main-dum}(V_i, T_i)$ is the waste dump maintenance cost, USD, $v_{main-pon}(V_i, T_i)$ is the tailings pond maintenance cost, USD, and $v_{dis}(V_i, T_i)$ is the cost of secondary geohazard prevention and soil and water conservation, USD.

The investment cost of ecological monitoring equipment and systems can be calculated using Equation (29):

$$v_{mon}(V_i, T_i) = c_{DM}[A_M(V_i) + A_D(V_i) + A_T(V_i) + A_B(V_i)]f_{dm} + c_{UW}A_M(V_i)f_{uw} + c_{WQ}n_{wq} \quad (29)$$

where c_{DM} is the unit cost of one set of dust monitoring equipment and associated system, USD/set, f_{dm} is the density of dust monitoring equipment sets per unit area, set/hm^2, c_{UW} is the unit cost of one set of groundwater monitoring equipment and associated system, USD/set, f_{uw} is the density of groundwater monitoring equipment sets per unit area, set/hm^2, c_{WQ} is the unit cost of one set of water-quality monitoring equipment and associated system, USD/set, and n_{wq} is the number of water-quality monitoring equipment, set.

The routine ecological monitoring and maintenance cost can be calculated using Equation (30):

$$v_{ope}(V_i, T_i) = [A_M(V_i) + A_D(V_i) + A_T(V_i) + A_B(V_i)]f_{dm}c_{dm}T_i + c_{uw}A_M(V_i)f_{uw}T_i + c_{wq}n_{wq}T_i \quad (30)$$

where c_{dm} is the annual operation and maintenance cost of one set of dust monitoring equipment and associated system, USD/set·a^{-1}, c_{uw} is the annual operation and maintenance cost of one set of groundwater monitoring equipment and associated system, USD/set·a^{-1}, and c_{wq} is the annual operation and maintenance cost of one set of water-quality monitoring equipment and associated system, USD/set·a^{-1}.

The waste dump maintenance cost can be calculated using Equation (31):

$$v_{main-dum}(V_i, T_i) = c_{mian-dum}\sum_{n=1}^{T_i} A_D(V_i, t) \quad (31)$$

where $c_{mian-dum}$ is the unit-area maintenance cost of the waste dump, USD/hm^2.

The tailings pond maintenance cost can be calculated using Equation (32):

$$v_{main-pon}(V_i, T_i) = c_{mian-pon}\sum_{n=1}^{T_i} V_T(V_i, t) \quad (32)$$

where $c_{mian-pon}$ is the maintenance cost per unit volume of tailings pond, USD/m^3, and $V_T(V_i, t)$ is the tailings volume deposited in the tailings pond at the end of year t, m^3.

The cost of secondary geohazard prevention and soil and water conservation included ecological protection measures for exposed surfaces of loose deposits, such as waste rock dumps, during the mining life. These measures included temporary protection measures such as laying vegetation mats, spraying plant fiber mulch, and constructing interception and drainage structures to control surface runoff. This cost also included the establishment of ecological buffer zones along the boundary of the disturbed mining area, such as mixed tree, shrub, and grass buffer belts with strong sediment interception capacity.

The cost of secondary disaster prevention and soil and water conservation can be calculated using Equation (33):

$$v_{\mathrm{dis}}(V_i, T_i) = c_{\mathrm{swc}} f_{\mathrm{swc}} \sum_{n=1}^{T_i} A_{\mathrm{D}}(V_i, t) + 0.2 c_{\mathrm{bou}} l_{bou} T_i \sqrt{\pi [A_{\mathrm{M}}(V_i) + A_{\mathrm{D}}(V_i) + A_{\mathrm{T}}(V_i)]} \quad (33)$$

where c_{swc} is the annual unit area cost of ecological soil and water conservation engineering for the waste dump, USD/(hm^2·a), f_{swc} is the proportion of the waste dump surface area requiring soil and water conservation measures, %, c_{bou} is the annual unit boundary length cost for establishing and maintaining ecological buffer zone, USD/(km·a), and l_{bou} is the width of the ecological buffer zone, km.

The post-closure reclamation cost mainly referred to the cost of measures used to restore the ecological functions of land damaged by mining after mine closed. The post-closure reclamation cost can be divided into the one-time reclamation cost at the initial reclamation stage and the maintenance costs during the reclamation period.

The post-closure reclamation cost can be calculated using Equation (34):

$$E_{\mathrm{R}}(V_i, T_i) = (c_{\mathrm{rec}} + c_{\mathrm{rec}}{}' T_{\mathrm{rec}})[A_{\mathrm{M}}(V_i) + A_{\mathrm{D}}(V_i) + A_{\mathrm{T}}(V_i) + A_{\mathrm{B}}(V_i)] \quad (34)$$

where c_{rec} is the one-time reclamation cost per unit area, USD/hm^2, $c_{\mathrm{rec}}{}'$ is the annual maintenance cost during the reclamation period, USD/(hm^2·a), and T_{rec} is the reclamation period, a.

In this study, the ecological cost was classified according to ecological impact type, occurrence stage, and cost attribute. The land occupation and associated ecosystem degradation cost was used only to account for the loss of land resource value and ecosystem service value caused by land occupation and ecological disturbance. Engineering costs for pollution treatment, monitoring, maintenance, and reclamation were not included in this component. The carbon emission cost was calculated based on the amount of carbon emissions generated during mining activities and the carbon trading price. This component includes direct and indirect carbon emissions caused by energy consumption, fuel use, explosive consumption, mineral processing, and the reduction in carbon sequestration caused by land disturbance. It was separated from the cost of land occupation and associated ecosystem degradation because it represents the carbon cost associated with mining activities, rather than the value loss of occupied land or ecosystem services. The environmental pollution control cost during the mining period was used only to account for the direct engineering expenditure required for dust control, wastewater treatment, and solid waste treatment or utilization during mine operation. Ecosystem service losses caused by land occupation, post-closure reclamation costs, and long-term monitoring costs were not included in this component. The ecological monitoring and maintenance cost was used only to account for routine monitoring, inspection, maintenance, and environmental management during mining and post-mining management. The post-closure reclamation cost was used only to account for the engineering expenditure required for land reshaping, soil covering, revegetation, and ecological restoration after mine closure. For components associated with multiple ecological disturbances, such as waste rock and tailings, their

occupied land area and the associated ecosystem service losses were included in the cost of land occupation and associated ecosystem degradation. Their pollution treatment or utilization costs were included in the environmental pollution control cost during the mining period. Their monitoring and maintenance requirements were included in the ecological monitoring and maintenance cost. Their subsequent restoration costs were included in the post-closure reclamation cost.

3. Case Study and Data Sources

3.1. Overview of the Study Mine

3.1.1. General Description of the Study Mine

A large open-pit iron mine was selected as the case study. The pit extends as a narrow and elongated belt with an approximately north-to-south trend. It is approximately 1660 m long in the north-to-south direction and approximately 1500 m wide in the east-to-west direction.

The ore is mainly composed of magnetite and martite, with subordinate hematite. The gangue minerals are dominated by quartz, with subordinate actinolite and tremolite, as well as minor hornblende and pyroxene. The iron ore is mainly characterized by a fine grained granoblastic texture, followed by a fibrous granular granoblastic texture. The ore structure is predominantly banded. The dark and light bands are mainly composed of iron minerals and quartz, respectively. The primary ore mineral is magnetite, which has been altered to hematite and martite by near-surface oxidation. From east to west, four orebodies, numbered I to IV, were identified. These orebodies occur as nearly parallel bands. They generally strike approximately north to south, dip westward, and have dip angles of 40–50°. However, their strike lengths, down-dip extensions, thicknesses, and morphologies vary. Orebody I is located on the eastern side of the mining area and extends through the northern, central, and southern sections. It has a total strike length of 8350 m and an average thickness of 60 m. Orebody II is located in the central part of the mining area. It has a total strike length of approximately 900 m and an average thickness of 45 m. This orebody shows a large down-dip extension, with a maximum controlled inclined depth of 680 m. Orebody III is distributed in the central and northern parts of the mining area. It has a total strike length of approximately 2800 m and a general thickness of 100–200 m and reaches a maximum controlled depth of 1600 m. Orebody IV is distributed in the central and northern part of the mining area, with a total strike length of 1600 m.

The ore in the mining area is mainly characterized by Fe and SiO_2. All ores in the deposit are classified as low-grade iron ore. The average geological grade of the measured ore is 28.55% TFe, with values of 28.49% TFe for magnetite ore and 29.24% TFe for martite ore. The average grade of subeconomic ore is 22.62% TFe. In the ultimate pit limit optimization conducted in this study, the cut-off grade was set at 20% TFe.

The designed ultimate pit limit extends for approximately 3 km, and the designed ore production capacity is 15 million t/a. The basic mine data were obtained from survey points in the mining area, production bench lines, peripheral topographic lines, engineering layout lines, surface structures, mining right boundary lines, and borehole data. The borehole data were first sorted and classified, and redundant data were removed or corrected. A borehole data structure was then established, including collar, survey, assay, and lithology tables. Subsequently, the borehole data were converted into the data structure required for modeling, and a borehole database was established. Based on the borehole database, composited sample database, and layered orebody plans, a three-dimensional orebody model of the mining area was constructed, as shown in Figure 2.

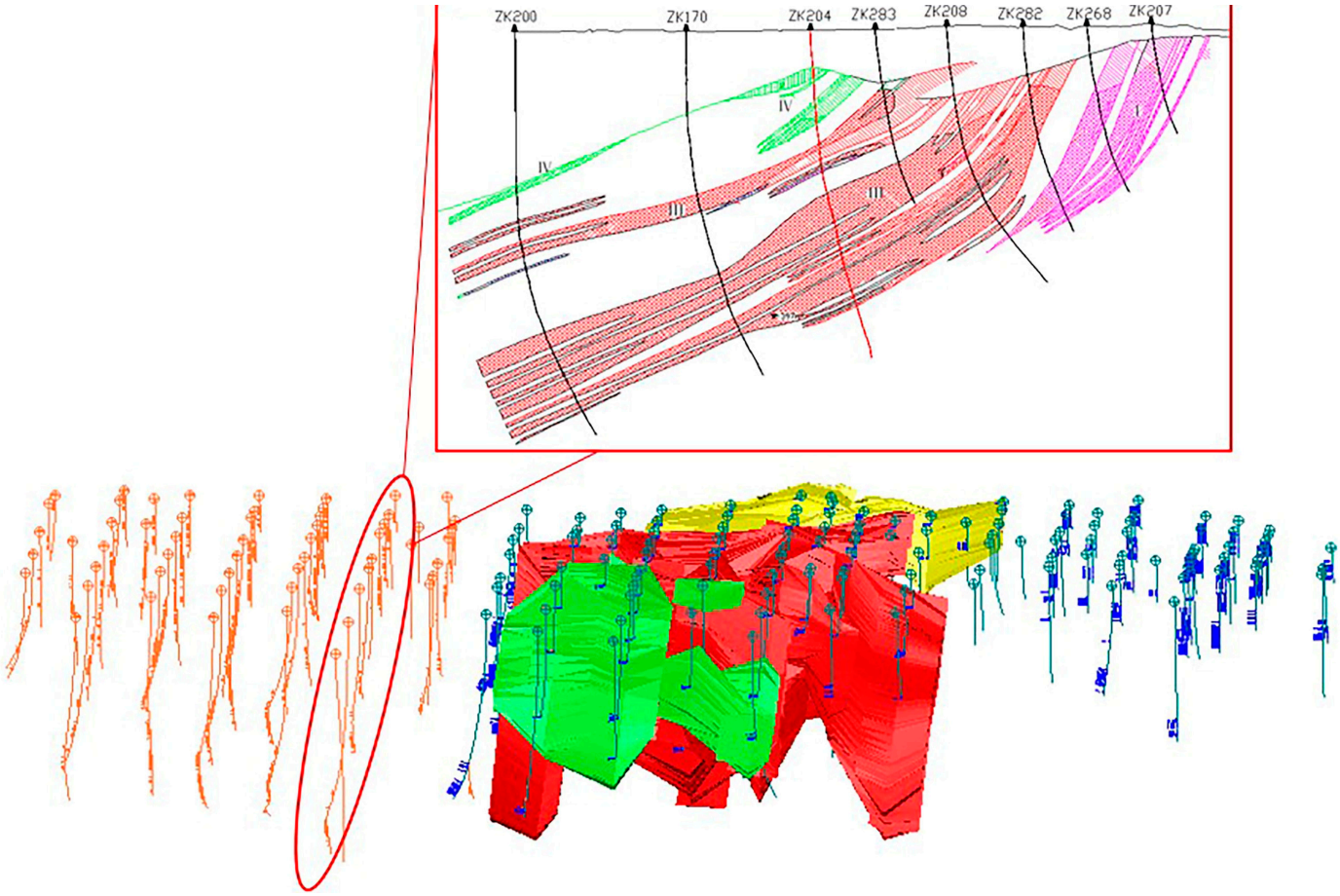


Figure 2. Drilling database and deposit model of the iron mining (partial model).

3.1.2. Technical and Economic Parameters of the Case Open-Pit Mine

The main drilling, loading, and haulage equipment included Φ310 mm and Φ250 mm rotary drills, 10 m^3 and 16.8 m^3 electric shovels, and 130 t and 180 t haul trucks. The technical and economic parameters required for ultimate pit limit optimization were determined based on the production data, as listed in Table 2.

Table 2. Technical and economic parameters of open-pit mining.

Mining Cost (USD/t)	Rock Stripping Cost (USD/t)	Processing Cost (USD/t)	Ore Extraction Rate (%)
10.54	2.49	10.25	93.3
Mineral Processing Recovery Rate (%)	**Concentrate Grade (%)**	**Dilution Rate (%)**	**Final Product Ore Price (USD/t)**
80	65	6	109.81

3.1.3. Scheme Design for Ultimate Pit Limits Under Different Slope Angles and Pit Scales

According to the orebody occurrence, lithological assemblages, structural characteristics, and engineering geological conditions of the slopes in the case mining area, the open-pit mine was divided into eight slope zones for the ultimate pit limit design (see Figure 3). The initial overall slope angles for each zone was listed in Table 3. The subsequent generation of pit limit schemes under different slope angle conditions was performed by using this initial slope angle combination as the reference scheme.

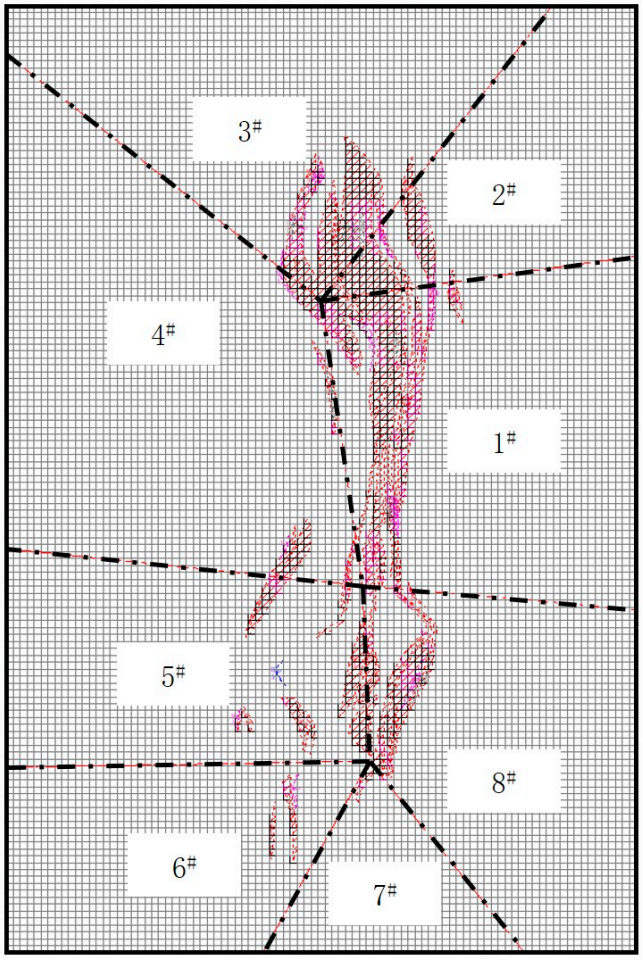


Figure 3. Spatial distribution of slope angle zones, where 1# refers to the 1# slope area, 2# to the 2# slope area, etc.

Table 3. Setting scheme of initial overall slope angles for the ultimate pit limit.

Region	1#	2#	3#	4#	5#	6#	7#	8#
Azimuth angle (°)	0.0	30.0	102.5	162.5	180.0	202.5	275.0	342.5
Overall slope angle (°)	39.0	40.5	42.0	44.5	47.0	46.0	45.0	42.0

To systematically analyze the effects of pit geometry changes on economic benefits and ecological disturbance, the slope angle and pit scale were selected as two key parameters controlling the ultimate pit limit geometry. Ultimate pit limit optimization was conducted using the negative floating cone elimination method [30]. This method was a floating cone-based ultimate pit limit generation method. A maximum potential pit was first constructed based on the block model, topographic surface, and slope angle constraints. Then, block groups with negative economic contributions were identified and removed while the required slope constraints were maintained. After this elimination process, the remaining block set forms a feasible candidate ultimate pit limit. The slope angle was used to characterize changes in the spatial slope configuration and external outline of the pit. The pit scale was used to represent the degree of resource extraction corresponding to the expansion or contraction of the ultimate pit limit. The variation in pit scale was represented by nested ultimate pit limit schemes. In the negative floating cone elimination method, an initial ultimate pit limit with the minimum required ore tonnage was first generated. Then, a fixed ore tonnage increment was added step-by-step to generate successive ultimate pit

limit schemes until the maximum feasible ultimate pit limit was reached. In this study, the ore tonnage increment between adjacent candidate ultimate pit limit schemes was set to 10 million t. Therefore, the variation in pit scale was represented by a series of nested ultimate pit limit schemes with gradually increasing ore tonnage, waste rock tonnage, stripping ratio, and disturbed land area.

On this basis, a two factor sensitivity analysis involving slope angle and pit scale was conducted using the control variable method. The analysis was designed to quantify the effects of zonal slope angle variation and pit scale change on economic benefits and ecological costs. The variation schemes of the slope angle in different zones were listed in Table 4. The values in square brackets indicate the variation range of the slope angle for the corresponding zone, while the slope angles of the other zones were kept at their initial values. During the sensitivity analysis of each zone, the slope angle of the target zone was increased step-by-step within the specified range at an interval of 1°. For each slope angle condition, nested ultimate pit limit schemes were generated by increasing the ore tonnage at a fixed increment. The variation in pit scale was represented. According to the above design and ore tonnage increment scheme, approximately 2000 candidate ultimate pit limit schemes were generated for subsequent analysis of economic benefit, ecological cost, and economic–ecological comprehensive benefit.

Table 4. Setting scheme of overall slope angles for the ultimate pit limit.

	1# Slope Angles (°)	2# Slope Angles (°)	3# Slope Angles (°)	4# Slope Angles (°)	5# Slope Angles (°)	6# Slope Angles (°)	7# Slope Angles (°)	8# Slope Angles (°)
1#	[39.0,48.0]	40.5	42.0	44.5	47.0	46.0	45.0	42.0
2#	39.0	[40.5,49.5]	42.0	44.5	47.0	46.0	45.0	42.0
3#	39.0	40.5	[42.0,51.0]	44.5	47.0	46.0	45.0	42.0
4#	39.0	40.5	42.0	[44.5,53.5]	47.0	46.0	45.0	42.0
5#	39.0	40.5	42.0	44.5	[47.0,56.0]	46.0	45.0	42.0
6#	39.0	40.5	42.0	44.5	47.0	[46.0,55.0]	45.0	42.0
7#	39.0	40.5	42.0	44.5	47.0	46.0	[45.0,54.0]	42.0
8#	39.0	40.5	42.0	44.5	47.0	46.0	45.0	[42.0,51.0]

All candidate ultimate pit limit schemes were generated using self-developed mine planning software based on the geological block model and predefined slope angle constraints. Approximately 2000 schemes were generated under different combinations of zonal slope angle and pit scale. The generation of ultimate pit limit schemes and ecological cost accounting required approximately 385 min on a workstation equipped with an i9 CPU. Because ecological cost accounting was performed after ultimate pit limit generation, its additional computational cost was limited. The main computational workload was associated with ultimate pit limit generation and the extraction of ore tonnage, waste rock tonnage, disturbed land area, energy consumption, and related engineering quantities.

It should also be noted that the generated ultimate pit limit schemes represent strategic level ultimate pit limit alternatives rather than detailed mine design schemes. Although slope angle constraints were incorporated into the pit limit generation process, detailed operational design factors, such as haulage roads, access ramps, and production scheduling constraints, were not explicitly modeled at this stage. In addition, the final slope angle was strongly affected by rock mass properties, discontinuities, hydrogeological conditions, and slope stability requirements. These geotechnical factors were not directly analyzed in this study, because the proposed approach was intended to provide a preliminary evaluation before detailed slope angle optimization and slope stability verification. The optimization potential of different slope angle zones was mainly quantified from economic and ecological

perspectives. Therefore, the results should not be regarded as a final geotechnical slope design. Instead, they should be used to identify candidate zones for further geotechnical assessment and slope optimization.

3.2. Parameters for Ecological Cost Accounting

Based on the regional ecological background of the case open-pit mining area, the mine production process, mine production process, technical parameters of mining and mineral processing, local statistical data, local charging standards and literature data, the basic parameters required for ecological cost accounting were determined. The parameter system mainly included land occupation and disturbance parameters, ecosystem service value parameters, energy consumption and carbon emission parameters, pollution control parameters, and ecological restoration parameters. These parameters were used to convert the ecological disturbances caused by different ultimate pit limit schemes into monetary values. The corresponding parameter values are listed in Table 5.

Table 5. Main parameters for ecological cost accounting for the case open-pit mine.

Formula Symbol	Unit	Value	Data Source	Formula Symbol	Unit	Value	Data Source
Δv_{yield}	USD/hm^2	351,288.06	Local statistical data	y_{npp}	t/(hm^2·a)	6.56	Regional ecological data
f_{O_2}	/	1.20	Regional ecological data	c_{O_2}	USD/t	95.14	Local charging standards
γ_w	t/m^3	2.70	Mine data	k_w	/	1.30	Mine data
f_D	/	1.85	Mine data	H_D	m	120	Mine data
g_P	%	65	Mine data	r_P	%	80	Mine data
H_T	m	100	Mine data	γ_T	t/m^3	1.75	Mine data
f_T	/	2.05	Mine data	a_{SO_2}	t/(hm^2·a)	33.20	Regional ecological data
c_{SO_2}	USD/t SO_2	456.67	Local charging standards	a_{dus}	t/(hm^2·a)	0.50	Regional ecological data
c_{dus}	USD/t	58.57	Local charging standards	s_r	t/(hm^2·a)	63.19	Regional ecological data
γ_s	t/m^3	1.40	Mine data	h_s	m	0.80	Mine data
y_s	USD/hm^2	4391.10	Local statistical data	p_r	mm/a	800	Local meteorological data
k_r	%	40	Local meteorological data	f_p	/	0.28	Regional ecological data
c_{wat}	USD/m^3	1.46	Local charging standards	k_N	%	0.531	Regional ecological data
k_P	%	0.042	Regional ecological data	k_K	%	0.201	Regional ecological data
$f_{P_2O_5}$	/	2.2903	Calculated constant	p_N	USD/t	497.66	Local charging standards
p_P	USD/t	439.11	Local charging standards	p_K	USD/t	585.48	Local charging standards
c_{sce}	USD/(hm^2·a)	0.88	Local statistical data	f_{cul}	/	0.20	Local statistical data
c_{car}	USD/t CO_2	10.98	Local statistical data	$e_{W1} + e_{W2}$	kWh/t	1.20	Mine data
e_{W3}	kWh/a	15,120,000	Mine data	η_e	t CO_2/kWh	0.0011082	Regional average electricity CO_2 emission factor
$d_{W2} + d_{W4}$	t/t	0.00056636	Mine data	η_{d1}	t CO_2/t	3.17	Regional average electricity CO_2 emission factor
η_{d2}	t CO_2/t	4.4409	Regional average electricity CO_2 emission factor	b_w	t/m^3	0.00092	Mine data
η_b	t CO_2/t	1.84	Regional average electricity CO_2 emission factor	m_w	kWh/t	28.50	Mine data
f_{CO_2}	/	1.62	Regional ecological data	p_t	%	100	Local statistical data
V_c	m^3	120,000	Mine data	V_b	m^3	3600	Mine data
cem_{CO_2}	t CO_2/m^3	0.29	Regional average electricity CO_2 emission factor	b_{CO_2}	t CO_2/m^3	15.70	Regional average electricity CO_2 emission factor
t_{w1}	t/m^3	0.002073	Mine data	t_{w2}	t/m^3	0.0305	Mine data
k_{bls}	t/t	0.000025	Mine data	c_{pitw}	USD/m^3	0.06	Mine data
k_{gw}	/	0.15	Mine data	c_{pro}	USD/m^3	0.16	Mine data
ω_{ore}	m^3/t	0.7	Mine data	ω_{per}	t/(person·a)	40	Mine data
c_{dom}	USD/m^3	0.11	Local charging standards	c_{DM}	USD/set	5122.95	Mine data
f_{dm}	set/hm^2	0.008	Mine data	c_{UW}	USD/set	1902.81	Local charging standards
f_{uw}	set/hm^2	0.003	Mine data	c_{WQ}	USD/set	21,955.50	Local charging standards
c_{dm}	USD/(set·a)	1463.70	Local charging standards	c_{uw}	USD/(set·a)	3659.25	Local charging standards
c_{wq}	USD/(set·a)	8782.20	Local charging standards	$c_{mian-dum}$	USD/hm^2	585.48	Mine data
$c_{mian-pon}$	USD/hm^2	219.55	Mine data	c_{swc}	USD/(hm^2·a)	1756.44	Mine data
f_{swc}	%	30	Estimate parameters	c_{bou}	USD/(km·a)	5854.80	Local charging standards
l_{bou}	km	0.02	Assuming parameters	c_{rec}	USD/hm^2	73,185.00	Estimate parameters
c_{rec}'	USD/(hm^2·a)	161.00	Estimate parameters	T_{rec}	a	5	Assuming parameters

3.3. Ecological Cost Sensitivity Analysis Under Carbon Trading Price

Carbon emission cost was an important component of the total ecological cost in open-pit mining. Since carbon emission cost was directly affected by the carbon trading price, fluctuations in the carbon trading price may change the accounting results of total ecological cost. To evaluate the influence of carbon trading price uncertainty on ecological

cost accounting, a sensitivity analysis was conducted under different carbon trading price scenarios in this study.

In the base scenario, the carbon trading price was set at 10.98 USD/t CO_2. To characterize moderate fluctuations in the carbon market, two additional carbon trading price scenarios were established by decreasing and increasing the base carbon trading price by 20%. Accordingly, the carbon trading prices in the low, base, and high carbon trading price scenarios were set at 8.78, 10.98, and 13.18 USD/t CO_2, respectively. Under each carbon trading price scenario, only the carbon emission cost of each candidate ultimate pit limit scheme was recalculated, whereas the other ecological cost components were kept constant.

4. Results

4.1. Profit Results Under Different Ultimate Pit Limit Geometries

According to the slope angle and pit scale control schemes defined in Section 3.1.3, approximately 2000 ultimate pit limit schemes were generated. Because a large number of ultimate pit limit schemes, Figure 4 showed the 3D geometries of selected representative ultimate pit limit schemes. The generated ultimate pit limit scheme set covered the main geometrical characteristics of ultimate pit limits under variations in zonal slope angles and pit scales. It can be used to systematically characterize the influence of zonal slope angle adjustment on pit profit. Based on this ultimate pit limit scheme set, the profit results of all candidate pit limit schemes were further statistically analyzed. The profit distributions under different slope angles and pit scales were shown in Figure 5.

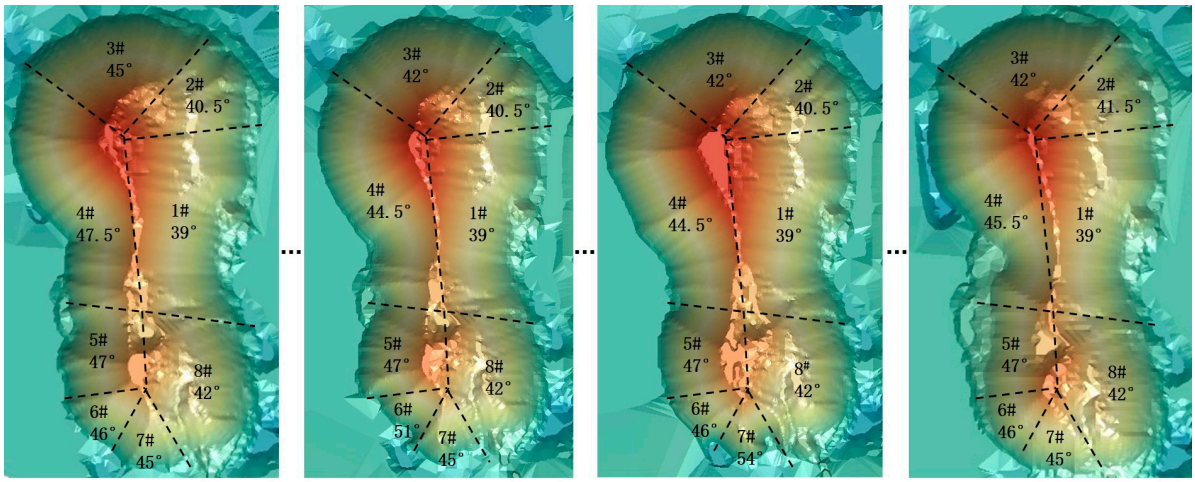


Figure 4. Three-dimensional geometries of some ultimate pit limit schemes.

Figure 5 shows the distribution of profits of the ultimate pit limit schemes under coupled variations in zonal slope angle and pit scale. In the figure, the x-axis represents pit scale, expressed as the total ore and waste rock tonnage. The y-axis represents slope angle, and the z-axis represents the profit of the candidate ultimate pit limit schemes. The profits of the candidate ultimate pit limit schemes generated under different slope angles and pit scales mainly range from USD 3200 million to USD 4100 million, with an overall profit variation of approximately USD 900 million. The pit scale determined the overall level of resource extraction and stripping workload, resulting in a clear peak shaped profit pattern. In contrast, variations in the slope angles of different zones have different degrees of influence on profit. The result indicated evident spatial heterogeneity in the ultimate pit limit optimization for open-pit mines with multiple slope zones.

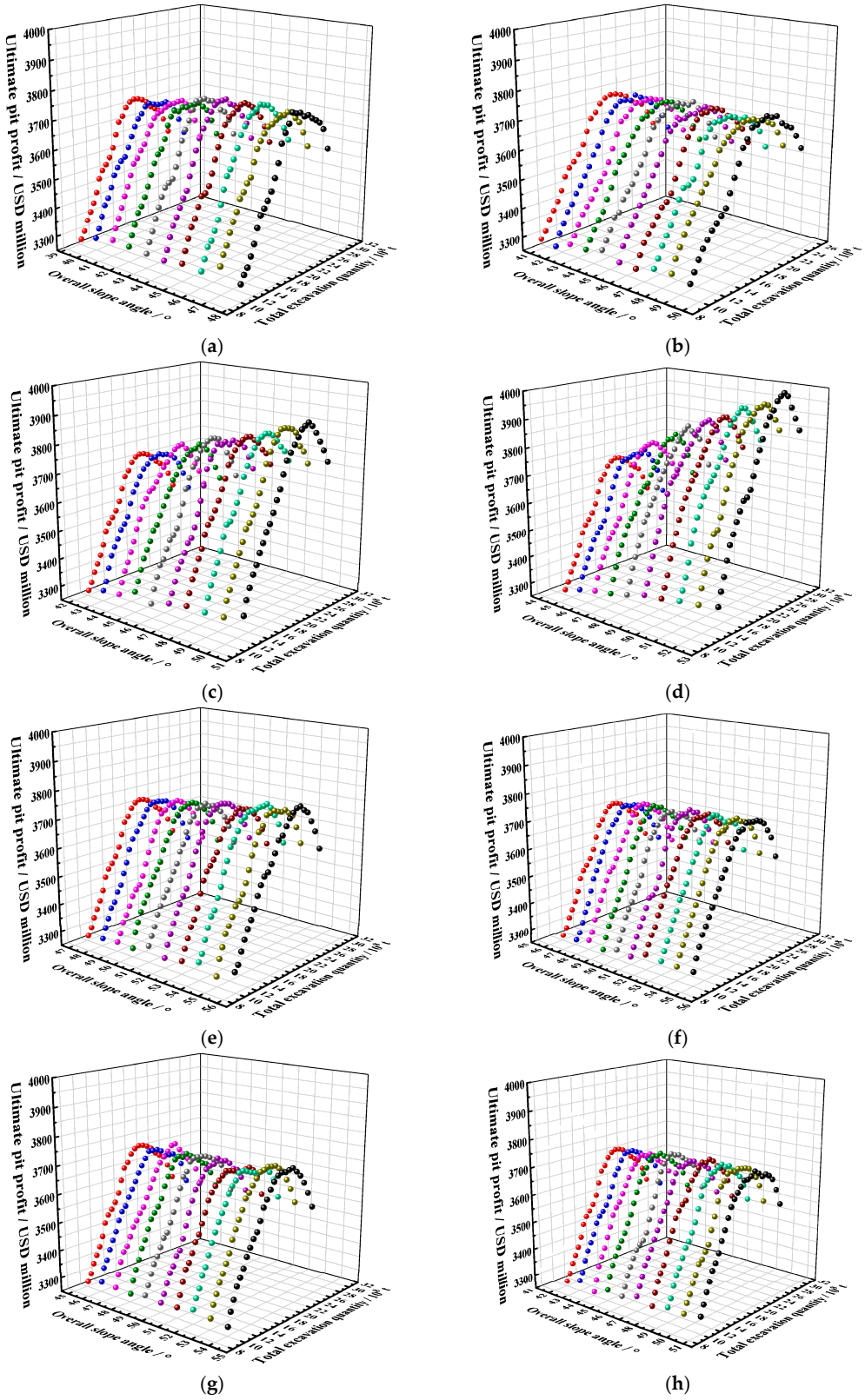


Figure 5. Distribution of total profits of candidate ultimate pit limit schemes under coupled variations in open-pit scale and zonal slope angle: (**a**) variation in the slope angle of Zone 1#; (**b**) variation in the slope angle of Zone 2#; (**c**) variation in the slope angle of Zone 3#; (**d**) variation in the slope angle of Zone 4#; (**e**) variation in the slope angle of Zone 5#; (**f**) variation in the slope angle of Zone 6#; (**g**) variation in the slope angle of Zone 7#; (**h**) variation in the slope angle of Zone 8#.

Within the set of ultimate pit limit schemes, both slope angle adjustment and pit scale variation affected the profit results of the ultimate pit limit schemes. As pit scale increases, the profits of pit limit schemes in all zones first increase and then decrease, indicating that pit profit does not increase monotonically with pit scale. At relatively small pit scales, outward expansion of the pit limit increases the amount of recoverable ore. The additional ore revenue exceeds the additional costs of waste rock stripping, mining, and mineral processing. Therefore, the profit increased with pit scale. However, as the pit scale continues to increase, the ultimate pit limit gradually expands into areas with less favorable ore and waste rock spatial relationships or higher stripping intensity. At this stage, the growth in additional ore revenue gradually weakened. In contrast, the costs of waste rock stripping volume, haulage workload, mining and mineral processing continue to increase. As a result, the profit growth slowed down and eventually declined.

The profit response caused by the progressive steepening of zonal slope angles can be divided into two categories. The first category included low sensitivity zones, where the increase in profit was relatively small as the slope angle was steepened. Only slight fluctuations were observed in some ultimate pit limit schemes, such as Zones 2#, 7#, and 8#. This result indicated that slope angle variations in these zones had a weak combined effect on the ore tonnage, waste rock tonnage, and stripping ratio within the ultimate pit limit. The internal ore and waste rock proportion was unlikely to be changed by zonal slope angle adjustment. Although slope steepening may reduce waste rock stripping to some extent, the resulting cost savings were insufficient to substantially increase the total profit. The second category included high sensitivity zones, where the profit increased more clearly as the slope angle was steepened, such as Zones 3# and 4#. This result indicated that slope angle variations in these zones could more effectively improve the ore and waste rock relationship within the ultimate pit limit. By maintaining or increasing recoverable ore tonnage while reducing waste rock stripping, the stripping ratio could be reduced and the profit could be increased.

4.2. Ecological Cost Analysis of Profit-Optimal Ultimate Pit Limit Schemes Under Different Slope Angle Combinations

Based on the analysis of the profit distribution of ultimate pit limit schemes in the previous section, the ecological costs corresponding to ultimate pit limit schemes were further evaluated. Under each slope angle combination, the ultimate pit limit schemes with the highest profit was selected as the profit-optimal ultimate pit limit scheme for that combination, and its ecological cost was then calculated using Equations (1)–(34). The ecological cost results of the profit-optimal ultimate pit limit schemes under different slope angle combinations were shown in Figure 6.

Figure 6 showed the ecological cost composition of the profit-optimal ultimate pit limit schemes under different slope angle combinations. The ecological costs corresponding to zonal slope angle variations mainly ranged from USD 1160 million to USD 1350 million. Although the total ecological cost did not show a completely monotonic trend under different zonal slope angle conditions, certain differences were still observed among the zones. In terms of ecological cost composition, the profit-optimal ultimate pit limit schemes showed a relatively consistent structure. Land occupation and associated ecosystem degradation cost accounted for the largest proportion of the total ecological cost, approximately 67.3%. Carbon emission cost ranked second, accounting for approximately 22.4%. In contrast, environmental pollution control cost during the mining period, ecological monitoring and maintenance cost, and post-closure reclamation cost contribute relatively small proportions, approximately 8.1%, 1.8%, and 0.4%, respectively. The variation in total ecological cost under different slope angle combinations can be mainly attributed to changes in cost components related to land occupation, ecosystem service loss, and carbon emissions caused by

variations in pit scale. In contrast, environmental pollution control, ecological monitoring and maintenance, and post-closure reclamation costs have relatively limited effects on the total ecological cost. This indicates that, under the profit maximization objective, the ecological cost of the ultimate pit limit schemes is mainly determined by the spatial disturbance intensity caused by pit expansion, rather than by changes in individual pollution control or management costs. Combined with the profit variation results shown in Figure 5, zones with stronger profit responses did not necessarily correspond to a simultaneous reduction in ecological cost. Taking Zones 3# and 4# as examples, slope steepening could increase profit, but the corresponding ecological cost remained at a relatively high level. Therefore, the profit-optimal ultimate pit limit scheme may overlook the ecological cost differences among different schemes.

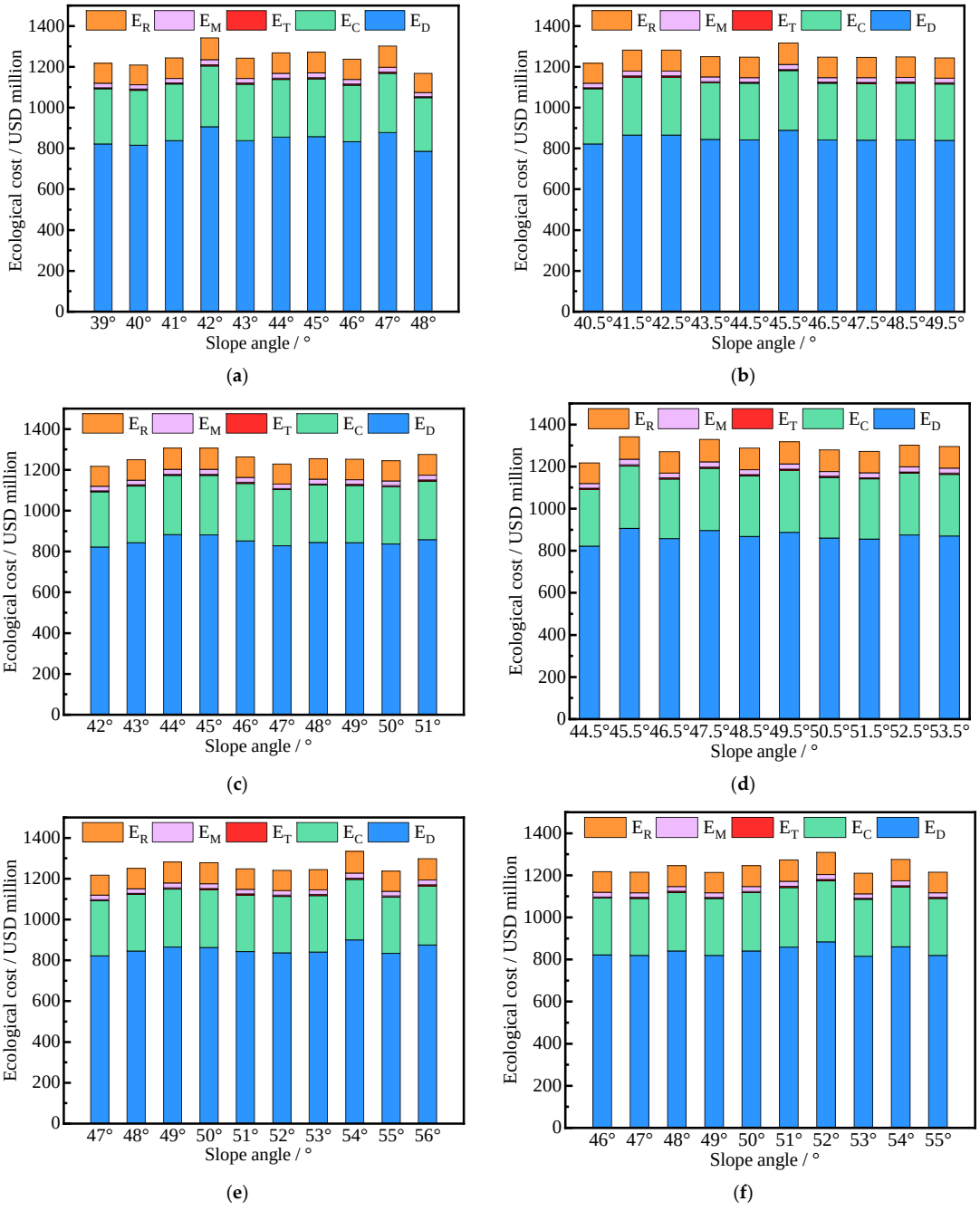


Figure 6. *Cont.*

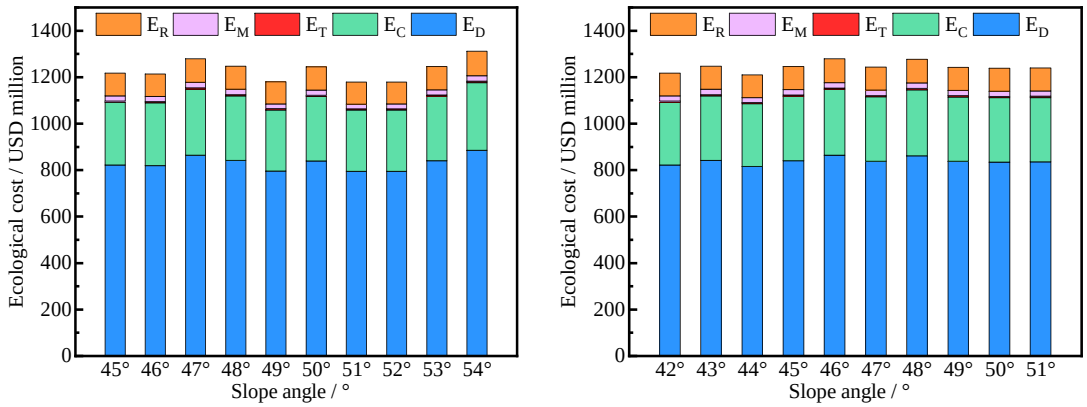


Figure 6. Ecological cost composition of the profit-optimal ultimate pit limit schemes under different slope angle combinations: (**a**) variation in the slope angle of Zone 1#; (**b**) variation in the slope angle of Zone 2#; (**c**) variation in the slope angle of Zone 3#; (**d**) variation in the slope angle of Zone 4#; (**e**) variation in the slope angle of Zone 5#; (**f**) variation in the slope angle of Zone 6#; (**g**) variation in the slope angle of Zone 7#; (**h**) variation in the slope angle of Zone 8#.

To further evaluate the influence of carbon trading price fluctuations on ecological cost accounting, the total ecological cost of the profit-optimal ultimate pit limit schemes was recalculated under different carbon trading price scenarios. Based on the base carbon trading price of 10.98 USD/t CO_2, two additional scenarios were established by decreasing and increasing the base value by 20%. Accordingly, the ecological cost results under the low, base, and high carbon trading price scenarios were shown in Figures 7 and 8.

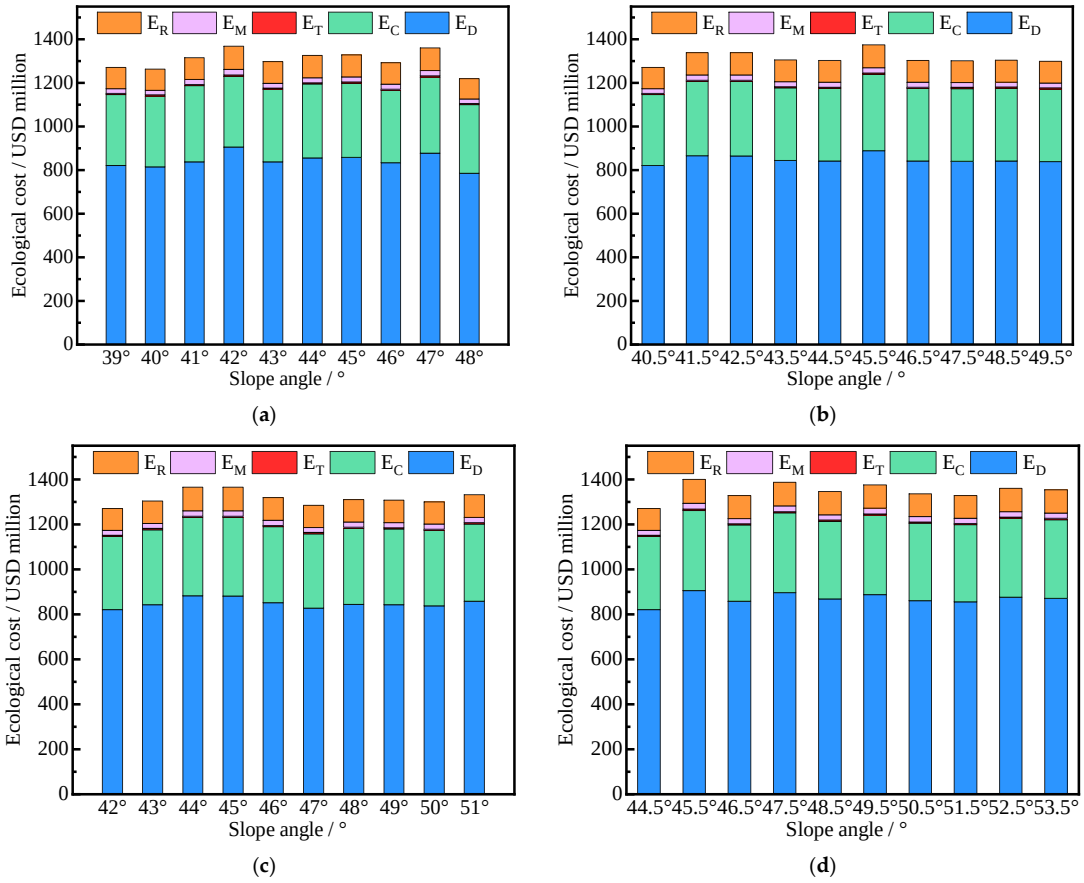


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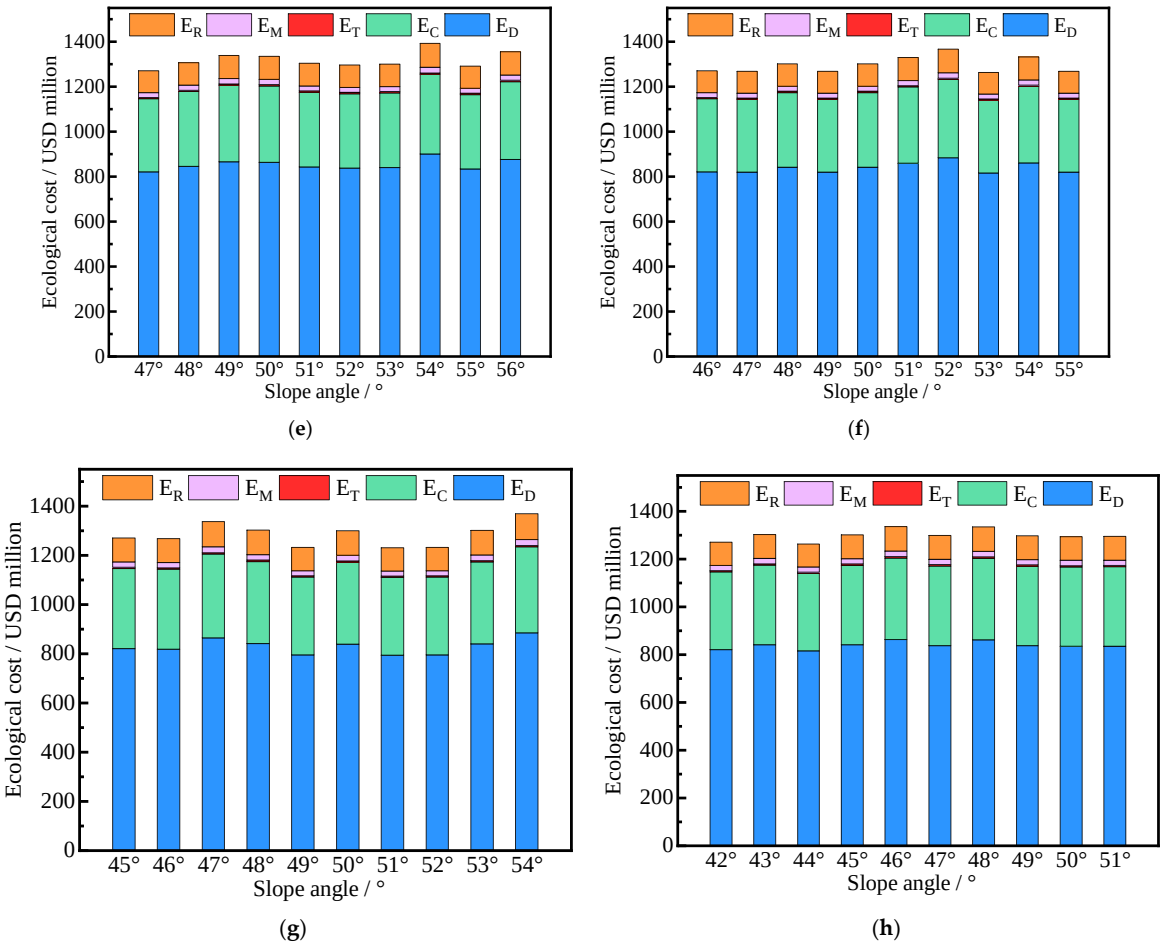


Figure 7. Ecological cost composition of the profit-optimal ultimate pit limit schemes under the high carbon trading price scenario with a 20% increase: (**a**) variation in the slope angle of Zone 1#; (**b**) variation in the slope angle of Zone 2#; (**c**) variation in the slope angle of Zone 3#; (**d**) variation in the slope angle of Zone 4#; (**e**) variation in the slope angle of Zone 5#; (**f**) variation in the slope angle of Zone 6#; (**g**) variation in the slope angle of Zone 7#; (**h**) variation in the slope angle of Zone 8#.

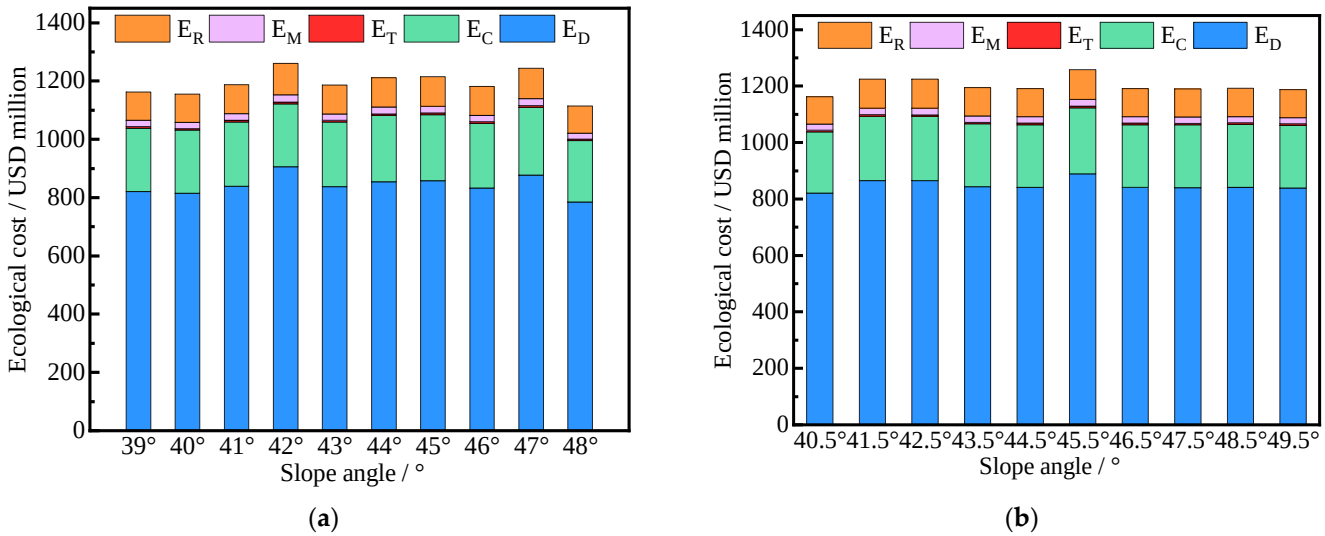


Figure 8. *Cont.*

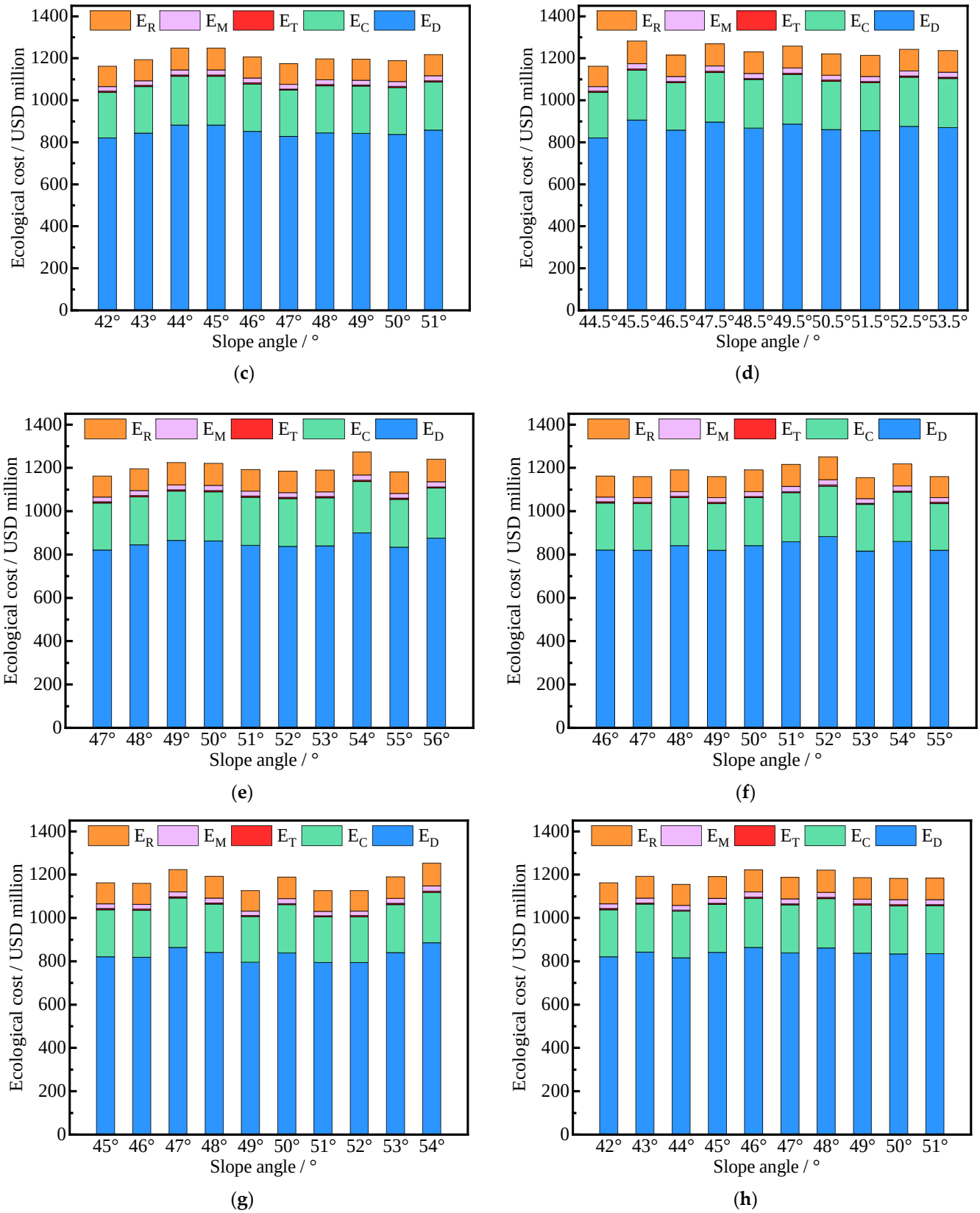


Figure 8. Ecological cost composition of the profit-optimal ultimate pit limit schemes under the low carbon trading price scenario with a 20% decrease: (**a**) variation in the slope angle of Zone 1#; (**b**) variation in the slope angle of Zone 2#; (**c**) variation in the slope angle of Zone 3#; (**d**) variation in the slope angle of Zone 4#; (**e**) variation in the slope angle of Zone 5#; (**f**) variation in the slope angle of Zone 6#; (**g**) variation in the slope angle of Zone 7#; (**h**) variation in the slope angle of Zone 8#.

Figures 7 and 8 showed the ecological cost composition of the profit-optimal ultimate pit limit schemes under the high and low carbon trading price scenarios, respectively. Compared with the base carbon trading price scenario shown in Figure 6, the total ecological cost increased under the high carbon trading price and decreased under the low carbon trading price. When the carbon trading price was increased or decreased by 20%, the average absolute fluctuation in total ecological cost was approximately USD 55 million to USD 56 million, corresponding to an average relative change of about ±4.4%. This result indicated that the total ecological cost was affected by carbon trading price variation, but the response magnitude was much smaller than the change in carbon trading price. This moderate response could be explained by the ecological cost composition. Under the base scenario, carbon emission cost accounted for approximately 22.4% of the total ecological cost. Therefore, carbon trading price variation mainly affected the carbon emission cost component rather than all ecological cost components. The sensitivity coefficient of total ecological cost to carbon trading price was approximately 0.22, suggesting that a 1% change in carbon trading price caused an average change of about 0.22% in total ecological cost. In addition, the ecological cost distribution patterns under different slope angle combinations were not fundamentally changed by carbon trading price fluctuations. Compared with the base scenario, a relatively uniform upward shift in total ecological cost was observed under the high carbon trading price scenario, whereas a relatively uniform downward shift was observed under the low carbon trading price scenario. The relative differences among different slope angle combinations remained generally consistent. This result indicated that carbon trading price fluctuations mainly changed the absolute magnitude of ecological cost, but did not change the basic distribution pattern of ecological cost among the profit-optimal ultimate pit limit schemes.

4.3. Economic–Ecological Comprehensive Benefit-Driven Selection of the Ultimate Pit Limit Scheme

In conventional evaluation, the optimal ultimate pit limit scheme was usually selected by maximizing profit. However, ecological effects related to land occupation, carbon emissions, pollution control, monitoring, and reclamation were not fully considered in the decision making process. In this study, the economic–ecological comprehensive benefit was used as the main indicator for comparing candidate ultimate pit limit schemes. This indicator was used because economic profit and ecological cost were measured in the same monetary unit. Therefore, ecological cost could be included directly in ultimate pit limit evaluation, and no additional weighting factor was required. The economic–ecological comprehensive benefit was calculated using Equation (35).

$$C_{EE}(V_i, T_i) = C_{Be}(V_i, T_i) - E_{total}(V_i, T_i) \quad (35)$$

where $C_{EE}(V_i, T_i)$ is the eco-economic comprehensive benefit cost of the pit limit V_i and $C_{Be}(V_i, T_i)$ is the economic profit of the pit limit V_i.

Figure 9 shows the distribution of economic–ecological comprehensive benefit of the candidates of the ultimate pit limit schemes under different combinations of open-pit scale and zonal slope angle. In the figure, the x-axis represents pit scale, expressed as the total ore and waste rock tonnage. The y-axis represents slope angle, and the z-axis represents the economic and ecological comprehensive benefit of the candidate ultimate pit limit schemes. The economic–ecological comprehensive benefit values of the candidates for the ultimate pit limit schemes were mainly distributed between USD 2000 million and USD 2600 million, with an overall variation of approximately USD 600 million. With the increase in open-pit scale, the economic–ecological comprehensive benefits of the ultimate pit limit schemes in all zones generally increased first and then decreased. Local maximum values were

observed within a certain range of open-pit scales. This trend was generally consistent with the variation in pit profit. However, after ecological costs were included, the peak positions of the economic–ecological comprehensive benefit curves shifted toward smaller pit scales. This shift indicated that the inclusion of ecological cost changed the marginal value of pit expansion. At relatively small open-pit scales, the additional ore revenue was higher than the increases in mining cost, stripping cost, and ecological cost. Therefore, the economic and ecological comprehensive benefit increased with open-pit scale. When the pit scale continued to expand, the increase in additional ore revenue gradually became smaller. In contrast, waste rock stripping, land occupation, carbon emissions, pollution control demand, ecological monitoring demand, and reclamation workload continued to increase. As a result, the growth rate of the economic and ecological comprehensive benefit decreased and eventually became negative.

Under similar pit scales, the responses of economic and ecological comprehensive benefit to zonal slope angle steepening could be divided into two groups. The first group included weak response zones, such as Zones 1#, 2#, 5#, 6#, 7#, and 8#. In these zones, only slight changes in economic and ecological comprehensive benefit were observed as the slope angle increased. Therefore, limited improvement in economic and ecological comprehensive benefit could be obtained through slope angle adjustment in these zones. The second group included strong response zones, such as Zones 3# and 4#. In these two zones, the economic–ecological comprehensive benefit of the candidates for the ultimate pit limit schemes increased more clearly as the slope angle was steepened. This results indicated that Zones 3# and 4# had relatively high economic–ecological comprehensive benefit response potential. Therefore, these two zones could be regarded as candidate zones for further geotechnical assessment and slope optimization, rather than as direct engineering recommendations for slope angle steepening.

Taking the initial slope angle combination as an example, the comparison between the ultimate pit limit scheme with the most economic–ecological comprehensive benefit and the profit-optimal ultimate pit limit scheme further showed the influence of ecological cost on ultimate pit limit selection. The total ore and waste rock tonnage of ultimate pit limit scheme with the most economic–ecological comprehensive benefit was 1376.369 million t. In comparison, that of the profit-optimal ultimate pit limit scheme was 1915.936 million t. After ecological cost was included, the selected pit scale was reduced by 539.567 million t, corresponding to a decrease of approximately 28.16%. The reduction in pit scale was mainly reflected in waste rock tonnage. The ore tonnage decreased from 508.700 million t in the profit-optimal ultimate pit limit scheme to 418.245 million t in the ultimate pit limit scheme with the most economic–ecological comprehensive benefit. The decrease was 90.455 million t, approximately 17.78%. In contrast, the waste rock tonnage decreased from 1407.236 million t to 958.124 million t. The decrease was 449.112 million t, approximately 31.91%. As a result, the stripping ratio decreased from 2.766 to 2.291. This result indicated that waste stripping was reduced more than ore extraction in the ultimate pit limit scheme with the most economic–ecological comprehensive benefit. Therefore, the ore and waste rock relationship within the selected ultimate pit limit was improved. Compared with the ultimate pit limit scheme with the most economic–ecological comprehensive benefit, a higher economic profit was obtained in the profit-optimal ultimate pit limit scheme because of its larger ore extraction scale. However, a higher ecological cost was also generated by this larger pit scale. The total ecological cost decreased from USD 1216.841 million in the profit-optimal scheme to USD 949.131 million in the ultimate pit limit scheme with the most economic–ecological comprehensive benefit. The reduction was USD 267.710 million, approximately 22.00%. The economic–ecological comprehensive benefit increased from USD 2494.440 million to USD 2540.201 million. The improvement was USD 45.761

million, approximately 1.83%. To further compare the ecological burden of the two schemes, the ecological cost/profit ratio was calculated. The economic profit of the profit-optimal ultimate pit limit scheme was USD 3711.281 million, and its ecological cost/profit ratio was 32.79%. In comparison, the economic profit of the ultimate pit limit scheme with the most economic–ecological comprehensive benefit was USD 3489.332 million, and its ecological cost/profit ratio was 27.20%. After ecological cost was included in scheme selection, the ecological cost/profit ratio was reduced by 5.59 percentage points. Although the economic profit decreased by USD 221.949 million, or approximately 5.98%, the total ecological cost decreased by USD 267.710 million, or approximately 22.00%. This result showed that a lower ecological cost burden per unit of economic profit was obtained in the ultimate pit limit scheme with the most economic–ecological comprehensive benefit.

Compared with conventional profit-optimal scheme, the included of ecological cost changed the scheme selection logic by modifying the marginal value of pit expansion. In a profit-optimal framework, pit expansion was mainly assessed according to the additional economic value of marginal ore blocks and the related mining cost. However, when ecological cost was included in the evaluation, each increment in pit scale also led to additional costs related to land occupation and associated ecosystem degradation, carbon emissions, environmental pollution control, ecological monitoring and maintenance, and post-closure reclamation. As the pit scale expanded, the marginal economic gain from additional ore extraction could gradually decrease. In contrast, the marginal ecological cost related to additional waste stripping and land disturbance could increase. Therefore, the scheme with the maximum economic–ecological comprehensive benefit did not necessarily correspond to the largest pit scale or the highest profit. Instead, the optimal scheme could shift toward a smaller and more compact ultimate pit limit than that selected based on profit alone. It should be emphasized that smaller pit scales were not simply favored by the proposed model. A smaller pit scale with insufficient ore recovery may not provide the highest economic–ecological comprehensive benefit. By contrast, an excessively expanded pit scale may generate high ecological costs due to increased stripping ratio, land occupation, waste dump area, tailings storage demand, carbon emissions, and reclamation burden. Therefore, the proposed model can be used to identify candidate ultimate pit limit schemes with relatively high economic return and relatively low ecological disturbance intensity.

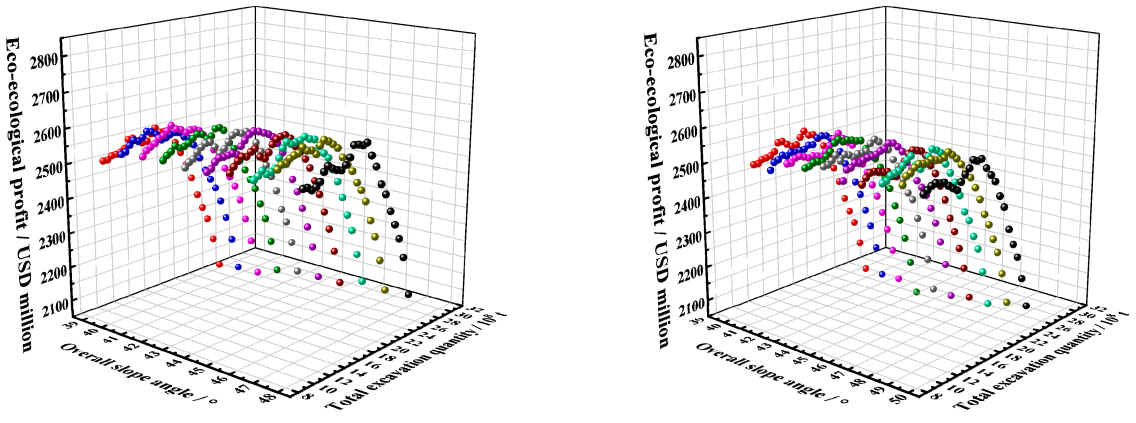


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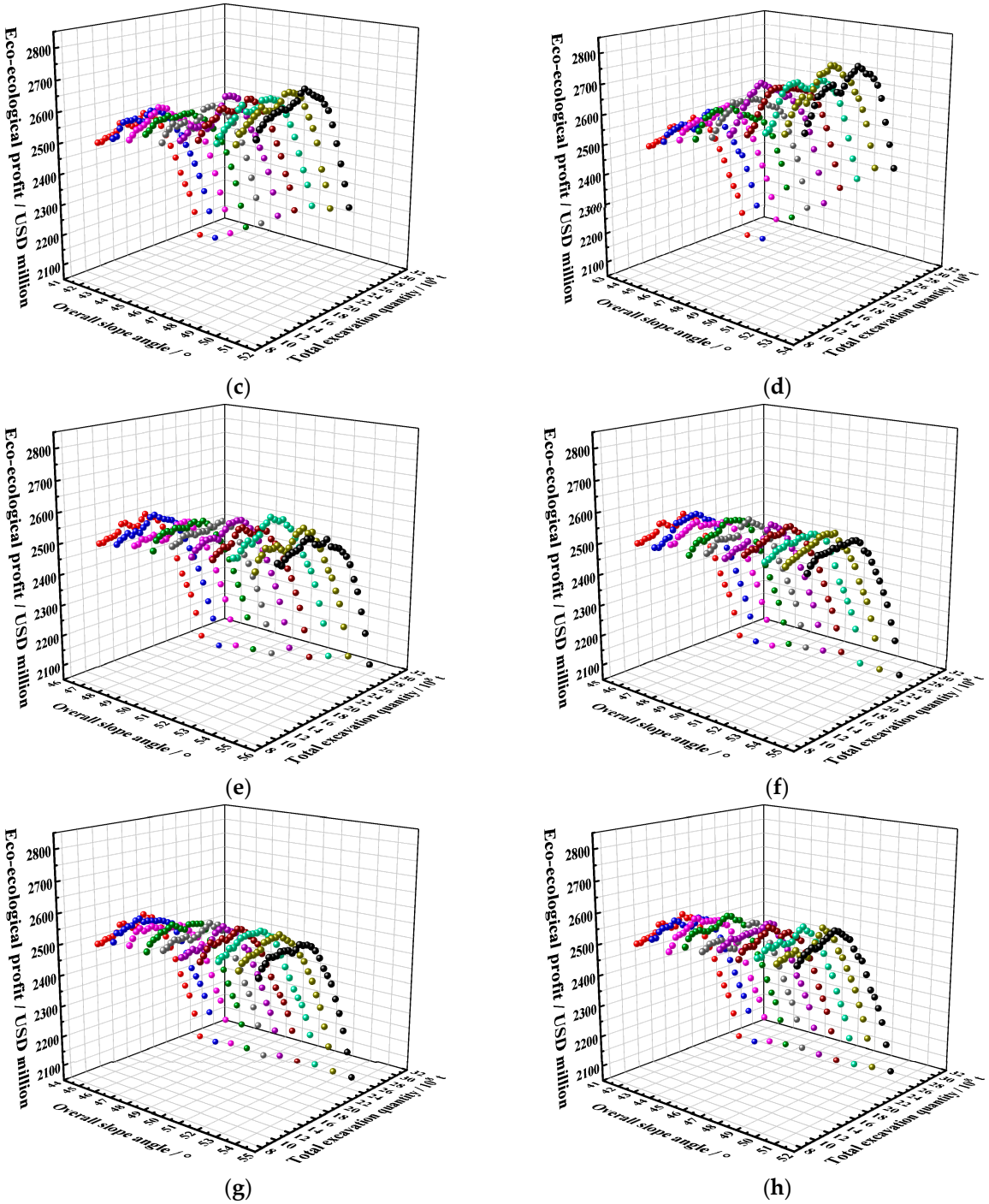


Figure 9. Distribution of economic–ecological comprehensive profits of ultimate pit limit schemes under coupled variations in open-pit scale and zonal slope angle: (**a**) variation in the slope angle of Zone 1#; (**b**) variation in the slope angle of Zone 2#; (**c**) variation in the slope angle of Zone 3#; (**d**) variation in the slope angle of Zone 4#; (**e**) variation in the slope angle of Zone 5#; (**f**) variation in the slope angle of Zone 6#; (**g**) variation in the slope angle of Zone 7#; (**h**) variation in the slope angle of Zone 8#.

This approach can also be used in mine planning with multiple objective. For example, economic profit, ecological costs, carbon emissions, and stripping ratio can be considered together when candidate ultimate pit limit schemes are screened. In this way, the ecological cost accounting model extends conventional optimization based only on profit by including ecological impacts into the mine planning process. It can provide support for green mine planning, ecological permitting, carbon management, and the comparison of alternative

ultimate pit limit schemes before detailed production scheduling and geotechnical design are carried out.

4.4. Slope Angle Optimization Potential Analysis Based on the Ecological Cost Accounting Model

To quantify the influence of progressive slope angle steepening in different zones on the economic–ecological comprehensive benefit of ultimate pit limit schemes, the ultimate pit limit scheme with the highest economic–ecological comprehensive benefit was extracted under each slope angle combination. The response of the comprehensive benefit to slope angle changes in the target zone was then analyzed. The result was conducted to reveal the sensitivity of the economic–ecological comprehensive benefit to zonal slope angle variations and to evaluate the optimization potential of different slope zones. The results were shown in Figure 10 and Table 6.

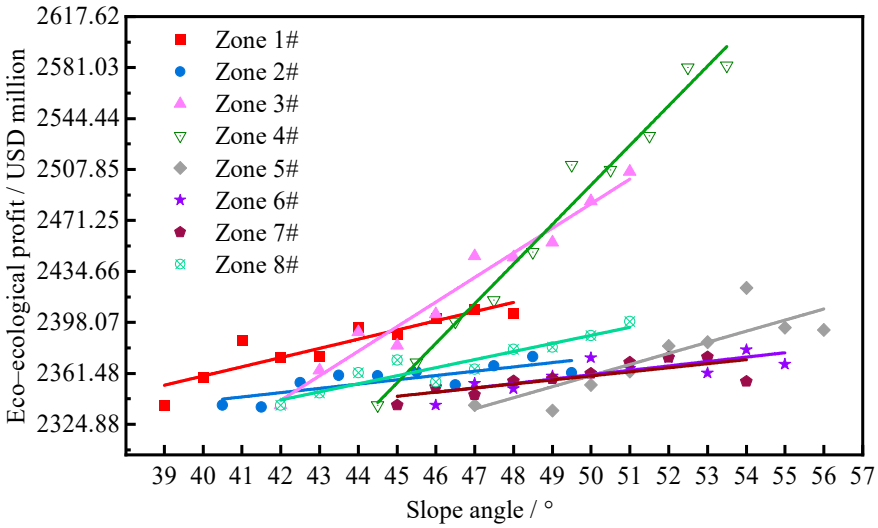


Figure 10. Variation curves of the maximum economic–ecological comprehensive benefits of candidate pit limit schemes during slope angle changes in different zones.

Table 6. Linear fitting results and response characteristics of the maximum profits under slope angle changes.

Zone	Linear Fitting Equation	R^2	95% CI of Slope	Interpretation
1#	y = 4514.316x + 1,568,130.791	0.831	2854.668–6173.965	Acceptable linear fit
2#	Not reported	0.652	849.630–3359.132	Weak linear fit
3#	y = 12,063.646x + 1,230,063.602	0.968	10,275.885–13,851.407	Strong linear fit
4#	y = 19,418.860x + 871,501.449	0.979	17,109.307–21,728.413	Strong linear fit
5#	y = 5443.356x + 1,476,741.741	0.751	2888.794–7997.919	Moderate linear fit
6#	Not reported	0.641	841.126–3478.464	Weak linear fit
7#	Not reported	0.606	684.963–3306.913	Weak linear fit
8#	y = 3958.128x + 1,570,716.995	0.880	2764.349–5151.908	Acceptable linear fit

Figure 10 showed the response characteristics of the optimal ultimate pit limit schemes selected based on economic–ecological comprehensive benefit during progressive steepening of slope angles in different slope zones. The slopes of the linear fitting equations for all zones were positive, indicating that the economic–ecological comprehensive benefit of the optimal ultimate pit limit schemes generally increased as the zonal slope angle was steepened. However, the magnitude of increase differed considerably among slope zones. This result suggested that the sensitivity of economic–ecological comprehensive benefit to slope angle variations was not consistent across different slope zones.

According to the linear fitting results, Zone 4# showed the largest fitted slope, with a value of 19,418.860, followed by Zone 3#, with a value of 12,063.646. These results indicated that for each 1° increase in slope angle, the economic–ecological comprehensive benefit of the corresponding optimal ultimate pit limit scheme increased in these two zones. Therefore, Zones 4# and 3# showed the highest sensitivity in terms of economic and ecological comprehensive benefit.

The slopes of Zones 5# and 1# were 5443.356 and 4514.316, respectively. Although these values were much lower than those of Zones 3# and 4#, they still indicated a certain positive response. In contrast, the slopes of Zones 8#, 6#, 2#, and 7# were relatively small, with values of 3958.128, 2159.795, 2104.381, and 1995.938, respectively, indicating that slope angle variations in these zones have relatively limited effects on the improvement of comprehensive benefit. The R^2 values for Zones 4# and 3# were 0.979 and 0.968, respectively. This result indicated that strong linear relationships were found between slope angle variation and economic–ecological comprehensive benefit in these two slope zones. Therefore, the variation patterns were relatively stable.

The stronger responses of Zones 3# and 4# can be further explained by the geological setting of the case mine. The main orebodies, including orebodies I to IV, are distributed as nearly north-to-south parallel bands. These orebodies dip westward at angles of approximately 40° to 50°. Under this geological setting, the effect of slope angle adjustment was different among the slope zones. In zones that were closely related to the dip direction and spatial extension of the main orebodies, slope angle steepening could more directly change the spatial relationship between the pit limit and the mineralized bodies. As a result, ore recovery, waste rock stripping, and the ore and waste rock relationship were more clearly affected.

Figure 11 showed the average increases in profit and economic–ecological comprehensive benefit for each 1° increase in slope angle in different slope zones. The average increases corresponding to Zones 4# and 3# were much higher than those in the other slope zones. Specifically, when the slope angle in Zone 4# was increased by 1°, the profit increased by an average of USD 41.38 million, while Zone 3# ranked second, with an average increase of USD 35.32 million. This result indicated that slope angle variations in these two slope zones had the strongest effect on improving the profit. Zones 1# and 5# showed intermediate responses, with average profit increases of approximately USD 8.32 million and USD 8.38 million, respectively, for each 1° increase in slope angle. In contrast, the average increases in pit profit for Zones 6#, 8#, 2#, and 7# were much lower, at approximately USD 3.46 million, USD 2.76 million, USD 1.75 million, and USD 1.63 million, respectively. In terms of economic–ecological comprehensive benefit, when the slope angle in Zone 4# was steepened by 1°, the comprehensive benefit increased by an average of approximately USD 27.11 million, followed by Zone 3#, with an average increase of approximately USD 18.62 million. This result indicated that, after profit and ecological cost were considered together, these two slope zones still play a dominant role in improving the comprehensive benefit of the ultimate pit limit schemes. The average increases in comprehensive benefit for Zones 1#, 8#, and 5# were approximately USD 7.34 million, USD 6.68 million, and USD 5.99 million, respectively, indicating relatively clear improvement effects. The average increases in comprehensive benefit for Zones 6#, 2#, and 7# are USD 3.27 million, USD 2.61 million, and USD 1.89 million, respectively, suggesting that slope angle adjustment in these zones has a relatively limited contribution to the improvement of economic–ecological comprehensive benefit.

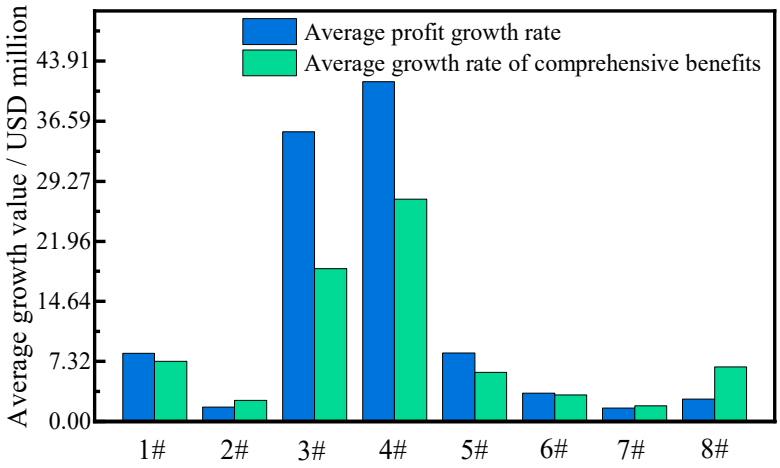


Figure 11. Distribution of the average increases in pit limit profit and comprehensive benefit when the slope angle in each zone is steepened by 1°.

A comparison between the profit indicator and the economic–ecological comprehensive benefit indicator shows that Zones 4# and 3# maintain the highest sensitivity under both evaluation criteria. This indicates that slope angle variations in these two zones exert strong control over the benefit of the ultimate pit limit schemes, and they should therefore be regarded as key zones for subsequent dynamic slope angle optimization and slope stability verification.

The applicability of the proposed ecological cost accounting model can be considered from three aspects. First, the model can be applied to the assessment of ecological disturbances in different types of open-pit mining, including coal mines, metallic mines, and non-metallic mines. Second, ultimate pit limit optimization can be supported by converting ecological impacts into ecological costs accounting model and incorporating them into the optimization process. Through this model, an optimal ultimate pit limit can be obtained under coordinated economic and ecological objectives. Third, the optimization potential of final slope angles can be evaluated by comparing the variations in economic profit, ecological cost, and economic–ecological comprehensive benefit under different slope angle schemes. The proposed model can be transferred to other types of open-pit mining, including open-pit coal mines, metallic mines, and non-metallic mines, because its accounting structure is based on the general ecological disturbance processes associated with open-pit mining. However, the parameter values should be recalibrated according to local ecological conditions, commodity type, mining method, land use pattern, carbon price, environmental regulations, and reclamation standards. Although the application to one iron open-pit mine demonstrates the feasibility of the proposed framework, it cannot fully represent the variability among different mining regions, commodities, and regulatory contexts. Therefore, the model should be further validated using multi-mine datasets and observed environmental expenditure records. In future applications, the calculated ecological costs should also be compared with actual reclamation budgets, carbon inventories, ecological compensation costs, and regulatory compliance expenses.

Several limitations should also be acknowledged. Necessary simplifications and assumptions are involved in the monetization of ecological impacts. Complex ecological processes are represented by several cost components, and some ecological effects are expressed as equivalent monetary values. In addition, parameters such as ecosystem service values, carbon prices, pollution control costs, and reclamation costs are affected by uncertainty and may vary with region, time, market conditions, and policy requirements. The calculated ecological cost and the resulting optimization scheme may therefore be

influenced by these uncertainties. A complete cost-item-based sensitivity decomposition was not conducted in this study. Such an analysis would require independent changes in several market prices, technical parameters, and ecological coefficients. These parameters include ecosystem service values, carbon trading price, emission factors, unit costs of pollution control, monitoring and maintenance costs, unit costs of reclamation, stripping ratio, energy consumption, disturbed land area, and tailings storage demand. The interactions among these factors may also affect the final ecological cost. Therefore, cost-item-based sensitivity decomposition should be treated as a systematic uncertainty analysis rather than a simple single factor calculation. In future work, a complete sensitivity analysis framework will be developed to quantify the contribution of each ecological cost item and each key parameter to changes in total ecological cost and economic and ecological comprehensive benefit.

5. Conclusions

The conclusions are as follows:

(1) Based on the DPSIR framework, an ecological cost accounting model was developed to evaluate the ecological disturbance of ultimate pit limit schemes. In this model, ecological costs are classified into five categories, including land occupation and associated ecosystem degradation cost, carbon emission cost, pollution control cost, ecological monitoring and maintenance cost, and post-closure reclamation cost. These cost items are converted into unified monetary values and are incorporated into the evaluation of ultimate pit limit schemes. This method allows ecological disturbance to be transformed from a traditional, external evaluation indicator into an endogenous variable participating in pit limit scheme selection, thereby providing a quantitative basis for shifting ultimate pit limit optimization from a single economic profit toward integrated economic–ecological decision making.

(2) The case study showed that, within the set of ultimate pit limit schemes constructed under different zonal slope angle and pit scale combinations, the total ecological costs of the schemes mainly range from USD 1160 million to USD 1350 million. The economic–ecological comprehensive benefits mainly range from USD 2000 million to USD 2600 million. After ecological costs were incorporated, the peak of economic–ecological comprehensive benefit shifted toward a smaller pit scale, indicating that the profit-optimal may lead to excessive pit expansion and overlook ecological costs associated with land disturbance, carbon emissions, and ecological restoration.

(3) Significant spatial differences were observed in the effect of zonal slope angle steepening on the economic–ecological comprehensive benefit of ultimate pit limit schemes. In the case of the open-pit mine, the highest sensitivity was found in Zones 4# and 3#. For each 1° increase in slope angle, average increases of approximately USD 27.11 million and USD 18.62 million in economic–ecological comprehensive benefit were obtained in Zones 4# and 3#, respectively. Therefore, these two zones were identified as candidate zones for further geotechnical assessment and slope optimization, rather than as direct engineering recommendations for slope angle steepening. The proposed economic–ecological comprehensive benefit evaluation can be used to support the selection of ultimate pit limit schemes. It can also be used for the preliminary identification of zones with relatively high economic–ecological optimization potential. These results provide a decision basis for green and efficient ultimate pit limit design in large open-pit mines with multiple slope zones.

(4) Future work should focus on coupling the proposed ecological cost accounting framework with slope stability verification and multi-objective optimization, so that economic benefit, ecological cost, carbon emissions, disturbed land area, stripping ratio, and geotechnical safety can be considered simultaneously. In addition, uncertainty analy-

sis of key parameters, such as carbon trading price, ecosystem service values, pollution control costs, and reclamation costs, should be strengthened. The model should also be further validated using field monitoring data, actual reclamation costs, carbon emission inventories, and environmental management expenditure records from different types of open-pit mines.

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