

RESEARCH ARTICLE

The Co-Evolutionary Interface: A Socio-Ecological Framework for Integrating Mineral Extraction and Recreational Development

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ABSTRACT

The transition from mineral extraction to post-mining land use is conventionally structured as a sequential process where recreational functions are introduced after extraction ceases. This temporal separation limits opportunities to incorporate long-term land-use objectives into active mine design and leaves unresolved questions regarding how industrial, ecological, and institutional functions can be coordinated across the mine life cycle. This conceptual paper develops the Integrated Interface Model (IIM), a framework for examining how mineral extraction and progressive landform transformation can be analyzed as interacting components of mine-transition planning. The framework synthesizes Social-Ecological Systems theory with the Industrial Sublime as complementary analytical perspectives, utilizing the Hyper-object concept to address the spatial scale and temporal complexity of surface mining landscapes. A conceptual theory-building methodology was conducted to identify structural relationships among mine-system processes, landform geometry, governance, and post-mining land transition. The Eden Project and Lusatian Lake District are examined as illustrative post-mining precedents that inform the model but do not constitute empirical validation of active extraction concurrent with public access. The resulting IIM organizes the interface across three dimensions: Spatial, concerning sectoral zoning (Z1-Z3) and geotechnical safety setbacks; Temporal, concerning deep-time hydrological phasing; and Institutional, concerning financial assurance through the Recreational End-Use Bond. Derived theoretical propositions concerning regulatory friction (P1), post-closure asset valuation (P2), and institutional trust (P3) are framed as hypotheses requiring future empirical, geotechnical, regulatory, and economic testing rather than established operational effects.

Keywords: Social-Ecological Systems; Industrial Sublime; Mine Transition; Hyper-object; Recreational Planning; Integrated Interface Model

1. Introduction

The dawn of the anthropocene has fundamentally re-calibrated the relationship between industrial necessity and ecological preservation. As human activity becomes the dominant force shaping the earth's geology and ecosystems, the traditional boundaries that once separated industrial resource extraction zones from pristine recreational landscapes are increasingly blurred^[1]. This shift creates a global land-use conflict characterized by spatial compression. The growing demand for critical minerals required for the global

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energy transition such as lithium, cobalt, and graphite, whose production could increase significantly by 2050^[2] collides directly with expanding societal demand for nature-based leisure, open space, and ecological connectivity^[3]. As urban centers expand and historical buffer zones decrease, the proximity between active surface mining operations and populated areas has narrowed^[4]. This proximity elevates local operational scrutiny and directly affects a mining firm's Social License to Operate (SLO)^[5].

Historically, mine-life planning has operated under a linear, sequential logic of *Exploration* → *Extraction* → *Closure* → *Restoration* (^[10]). Under this temporal model, post-mining land-use objectives including public recreation, ecological restoration, or community assets are deferred until extraction and primary decommissioning have concluded. Existing literature highlights three major limitations inherent to this sequential approach:

i. **Temporal Delay:** Decades of operational activity elapse before a site is returned to public or ecological use, representing a protracted loss of local landscape access^[6].

ii. **Ecological and Structural Rigidity:** Standard post-mining reclamation often aims to construct basic vegetation covers or generalized green spaces^[7]. These standard landforms may underutilize the unique, high-relief topographies (e.g., deep pits, vertical wall sections, steep terraces) created by open-pit extraction that could otherwise support specialized adventure or high-intensity recreation^[8].

iii. **Planning Isolation:** Treating post-closure land use as a terminal phase rather than an integrated operational input can lead to redundant earthmoving costs, unaligned landforms, and missed opportunities for early community engagement^[9].

In response to these challenges, contemporary research emphasizes the importance of integrating post-mining objectives directly into active mine lifecycle planning^[9,10]. However, theoretical frameworks that systematically address how active extraction, spatial layout, safety boundaries, and post-closure functional objectives interact across time remain underdeveloped. To address this analytical gap, this conceptual paper synthesizes existing land-use, social-ecological, and spatial planning theories to propose the Integrated Interface Model (IIM). The IIM provides a conceptual framework for examining how mineral extraction and recreational development can be planned as interacting socio-ecological components across a mine's life cycle. The framework integrates Social-Ecological Systems (SES) theory^[11,12] with the concept of the Industrial Sublime^[13,14] to evaluate both the functional-metabolic and cultural-perceptual dimensions of large open-pit landscapes. Additionally, it applies the Hyper-object concept to address the spatial scale, temporal persistence, and physical impact of modern mining operations^[15].

Rather than asserting empirically established outcomes or guaranteed financial/regulatory performance, this paper formulates the IIM as a set of testable theoretical propositions organized across three core dimensions:

1. **Spatial Dimension:** Examining intentional topographical engineering during active extraction to explore potential spatial co-existence.

2. **Temporal Dimension:** Exploring opportunities for progressive, coexisting, or parallel site transition across operational phases.

3. **Institutional Dimension:** Evaluating governance and financial mechanisms, such as proposed Recreational End-Use (REU) Bonds, as conceptual tools to align active operations with long-term land-use planning.

The framework draws conceptual insights from prominent global post-mining precedents, such as the Eden Project (United Kingdom) and the Lusatian Lake District (Germany). Importantly, these cases serve as

illustrative landscape re-adaptation precedents rather than empirical proof of concurrent active extraction and public access. The primary goal of this article is to establish a rigorous theoretical foundation and outline a structured research agenda for future empirical testing in integrated mine-transition planning.

2. Theoretical Framework

2.1. Social-Ecological Systems (SES) Theory and Mine Lifecycle Governance

To analyze the interaction between mineral extraction and post-mining land use, this study applies the Social-Ecological Systems (SES) framework established by Ostrom^[11] and expanded by Folke et al.^[12]. Open-pit mining operations are not merely technical or industrial processes; they represent high-intensity interventions within complex socio-ecological systems. Within Ostrom's^[11] multi-tier framework, an active surface mine is modeled directly through core subsystem variables. The Resource System (RS) encompasses the mineralized geological formation, surrounding watershed, and physical landscape topography. The Resource Units (RU) comprise extracted mineral commodities, overburden materials, surface water volumes, and available land surface areas. The Governance Systems (GS) consist of national mining codes, regional environmental protection agencies, local land-use zoning, and formal or informal community agreements. The Actors (A) include mining operators, regulatory authorities, local community members, recreation advocacy groups, and post-closure land managers. The mine lifecycle is deconstructed into formal SES constructs in **Table 1**, mapping physical mining assets directly to Ostrom's^[11] subsystem variables.

Table 1. Institutional and Governance Deconstruction of Open-Pit Mine Subsystems.

SES Subsystem Variable	Operational Mine Component / Landscape Feature	Institutional & Ecological Governance Function	Primary Actor Interactions (A)	Author
Resource System (RS)	Geological ore body, overburden strata, pit void, and local watershed	Defines physical boundaries, structural stability limits, and baseline hydrological capacity	Mining engineers, hydrologists, environmental protection agencies	[11]; [12]; [16]
Resource Units (RU)	Extracted ore, waste rock/tailings, usable land surface, and surface water	Governs material flow rates, waste storage footprint, and post-mining land allocation	Mine operators, mineral processing teams, local land planners	[11]; [17]
Governance System (GS)	Mining codes, environmental laws, municipal zoning, and community agreements	Establishes compliance baselines, reclamation standards, and Social License to Operate (SLO)	Regulatory bodies, local government councils, corporate ESG officers	[11]; [12]; [16]
Actors (A)	Mining companies, regulatory authorities, local residents, and recreation groups	Participates in multi-stakeholder feedback loops to determine post-closure land utility	Community leaders, recreational advocacy coalitions, post-closure managers	[11]; [12]; [17]

Under formal SES theory, system feedback loops are governed strictly by institutional rules, material flow dynamics, and empirical ecosystem responses^[11,12]. Traditional mine planning routinely treats the GS and A as external operational constraints or downstream compliance hurdles to be managed sequentially near

lease expiry^[16]. By contrast, an integrated SES approach conceptualizes RS and RU as co-evolving with governance rules and stakeholder values across active extraction timelines^[11]. Integrating recreational and ecological end-uses during active extraction requires continuous feedback mechanisms where spatial monitoring data and community land-use priorities directly inform active pit geometry, overburden placement, and progressive landform design^[16,17]. Furthermore, establishing ecological baselines such as surface soil stabilization, watershed drainage management, and toxic contamination containment functions as a mandatory structural prerequisite within the SES framework before public access, community infrastructure, or recreational utility can be legitimately considered^[17].

2.2. The Industrial Sublime

While SES theory provides a structural framework for resource governance, evaluating the recreational potential of open-pit mining landscapes requires engaging with human perception and landscape aesthetics. This study incorporates the concept of the Industrial Sublime, rooted in aesthetic philosophy^[13] and modern landscape scholarship^[14]. The sublime describes a psychological state triggered by landscapes or structures that evoke awe, vastness, power, and a sense of solemn magnitude. Large open-pit mines with their terraced wall geometry, massive physical depth, and high visual contrast represent quintessential modern industrial sublime landscapes. Conventional mine reclamation frequently attempts to smooth or erase these dramatic topographies, attempting to return open-pit voids to generalized green spaces or basic ecological facsimiles^[7,8].

To ground aesthetic theory in physical mine planning, **Figure 1** demonstrates how perceptual features of the Industrial Sublime are directly translated into high-relief rock wall preservation, bench terracing, and buffered spatial access zones. First, regarding topographical preservation, rather than regrading all vertical wall sections, stable, high-relief rock faces can be intentionally engineered during active mining to preserve dramatic visual geometries suitable for climbing or high-intensity sports^[8]. Second, in terms of visual terracing, operational benches can be designed with long-term structural stability in mind, serving as prospective viewing platforms, trails, or amphitheaters. Third, through controlled proximity, spatial zoning can create safe visual access points, allowing visitors to experience the vast scale of the landscape while maintaining strict safety buffers away from active extraction equipment. By leveraging the unique scale and geometry of open-pit extraction, the Industrial Sublime transforms perceived environmental disruption into a distinct recreational and cultural asset, provided safety and ecological stability are maintained.

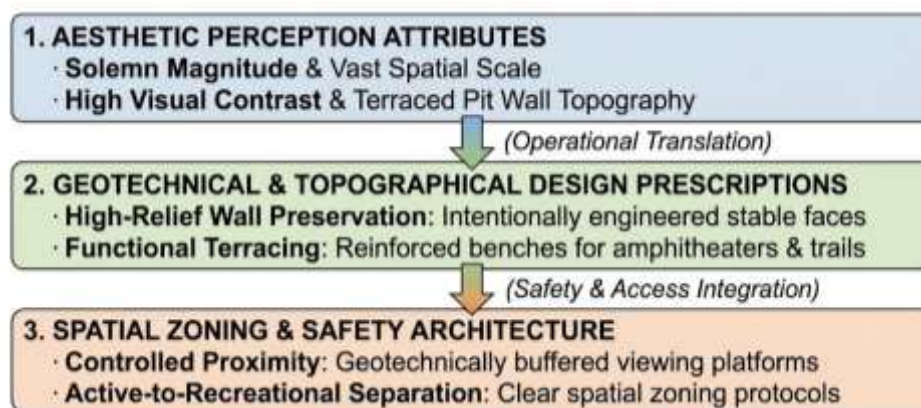


Figure 1. Industrial Sublime Landform Engineering Framework.

2.3. The Hyper-Object Concept

To address the sheer scale, environmental persistence, and multi-generational footprint of open-pit mining operations, this framework incorporates Morton's^[15] concept of the Hyper-object. A hyper-object is defined as an entity so massively distributed in time and space that it defies brief human temporal scales and localized spatial boundaries^[19]. Large open-pit mines exhibit hyper-object characteristics due to their decadal operational lifespans, permanent geological modifications, and centuries-long post-closure environmental legacies, such as pit lake hydrology and acid mine drainage monitoring. Rather than functioning purely as a theoretical concept, **Figure 2** illustrates how Hyper-object dynamics are operationalized across three concrete decision-making axes: century-scale landform stability, cumulative watershed spatial modeling, and long-term automated monitoring infrastructure. In deep-time landform planning, recognizing that pit geometries persist across centuries requires operators to design final pit slopes, bench stability, and drainage pathways during active mining rather than treating slope stability purely as a short-term operational requirement. Regarding cumulative spatial dynamics, operational modeling must account for how localized earthmoving during active extraction aggregates over time to shape regional hydrological and ecological corridors, preventing permanent spatial fragmentation. Finally, in terms of institutional continuity and monitoring, acknowledging the multi-generational lifespan of mining landforms necessitates continuous, long-term monitoring infrastructure, such as automated geotechnical sensors and hydrological tracking, alongside enduring financial mechanisms like long-term end-use bonds that outlast short-term corporate cycles.

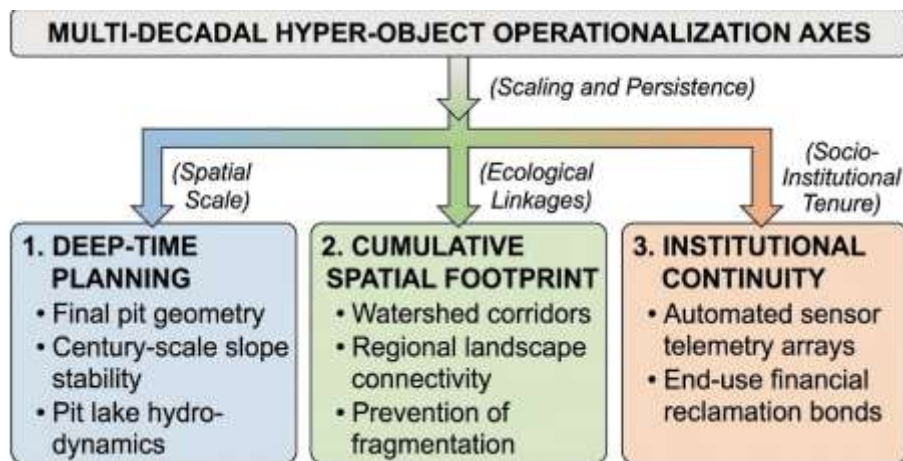


Figure 2. Operationalization of Hyper-Object dynamics across deep-time engineering, regional spatial footprints, and perpetual institutional monitoring regime.

2.4. Conceptual Synthesis: Theoretical Integration of the Model

The integration of Social-Ecological Systems theory, the Industrial Sublime, and Hyper-object dynamics forms the theoretical foundation of the Integrated Interface Model (IIM). Rather than relying on simple metaphorical links, these three perspectives provide complementary, non-overlapping analytical functions. As conceptualized in **Figure 3**, the Integrated Interface Model (IIM) structures the planning workflow by sequentially building upon Ostrom's SES governance baselines, applying Industrial Sublime topographical engineering, and scaling decision-making via Hyper-object temporal dynamics. Furthermore, to ensure these theoretical concepts translate into active operations, **Table 2** details the explicit engineering prescriptions, ecological preconditions, and long-term governance deliverables generated by each theoretical

lens. By unifying institutional governance, perceptual design, and multi-generational scale management, this theoretical framework provides a structured foundation for formulating testable research propositions regarding integrated mine lifecycle planning.

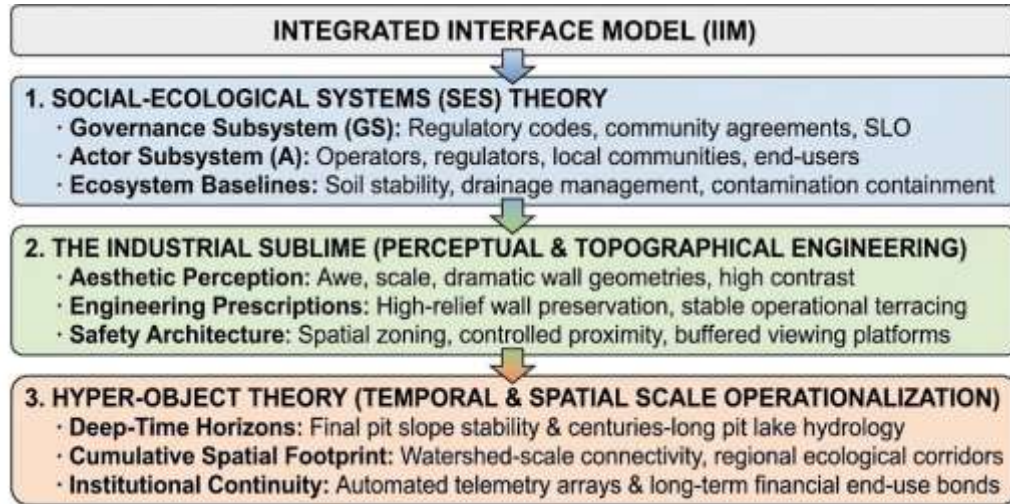


Figure 3. Operationalization workflow of the Integrated Interface Model (IIM).

Table 2. Operationalization Matrix Translating Theoretical Constructs into Mine Engineering Deliverables.

Theoretical Construct	Primary Analytical Lens	Engineering & Design Prescriptions	Ecological & Governance Deliverables	Author
Social-Ecological Systems (SES)	Institutional multi-tier rules and socio-ecological feedback loops	Sequential overburden placement, backfilling, and integrated slope grading during active mining	Soil stabilization baselines, water contamination containment, and co-managed land agreements	[11]; [12]; [16]; [17]
Industrial Sublime	Human landscape perception, scale, and high visual contrast	Selective high-relief rock wall preservation, stable bench terracing, and buffered access trails	Public viewing amphitheaters, rock-climbing faces, and safe recreational access zones	[13]; [14]; [8]; [7]
Hyper-Object Theory	Deep-time temporal persistence and regional footprint scale	Century-scale slope stability design, deep-pit lake hydrodynamic modeling, and corridor alignment	Automated geotechnical sensor telemetry, perpetual water treatment funds, and long-term end-use bonds	[15]; [16]; [17]

3. Methodology

3.1. Methodological Approach

To address the complex, multi-dimensional challenges of mine lifecycle planning, this study adopts a conceptual theory-building approach rather than an empirical or grounded theory research design. Conceptual synthesis is appropriate when existing theoretical domains such as Social-Ecological Systems

(SES) governance, landscape aesthetic theory, and temporal scale theory remain fragmented across disparate disciplines^[19,20]. While prior iterations of this work referenced grounded theory heuristics, this study does not draw upon a primary qualitative dataset, formal interview transcript coding, theoretical sampling, or constant-comparative field procedures. Instead, the methodology relies on integrative literature synthesis and theoretical operationalization^[21]. By systematically combining Ostrom's^[11] SES framework, the Industrial Sublime, and Morton's^[15] Hyper-object theory, the objective is to build a structured conceptual framework, the Integrated Interface Model (IIM) that generates testable propositions for mine design, safety zoning, and long-term land-use governance. The structural relationship between these analytical phases is summarized in **Table 3**.

Table 3. Methodological Structure and Function of Study Components.

Methodological Phase	Primary Source Material / Analytical Lens	Methodological Function	Scope & Analytical Boundaries	Author
1. Theoretical Synthesis	Interdisciplinary literature on SES, Industrial Sublime, Hyper-objects	Integrative theory building and variable operationalization	Conceptual formulation; does not constitute primary qualitative or quantitative data collection	[11]; [13]; [14]; [15]; [19]; [20]; [21]
2. Conceptual Operationalization	Mine engineering, geotechnical safety, and environmental governance literature	Mapping theoretical constructs to physical design prescriptions and governance mechanisms	Formulates testable propositions; requires site-specific economic and safety verification	[16]; [17]
3. Illustrative Benchmark Precedents	Secondary literature on Eden Project (UK) and Lusatian Lake District (Germany)	Contextual benchmarking of post-mining landform transformation	Demonstrates post-closure feasibility; does <i>not</i> validate active-mine parallel processing	[8]; [7]; [22]

3.2. Synthesis Protocol and Literature Selection Strategy

The conceptual framework was developed using a structured, three-stage literature selection and synthesis protocol^[21], detailed systematically in **Table 3**. First, a multi-database search was conducted across Scopus, Web of Science, and Google Scholar targeting four intersecting thematic domains: (1) social-ecological systems and mine governance; (2) open-pit mine geomorphology and landform engineering; (3) industrial landscape aesthetics and public perception; and (4) deep-time environmental legacy planning. Search terms included combinations of "*Social-Ecological Systems*," "*mine closure*," "*progressive reclamation*," "*industrial sublime*," "*hyper-object*," "*mine site safety zoning*," and "*closure financial assurance*."

Second, identified literature was screened based on conceptual relevance and analytical rigor. Priority was given to peer-reviewed studies that provided concrete governance parameters, geotechnical design criteria, or institutional frameworks. Purely descriptive heuristics, unverified biological analogies, and non-peer-reviewed commentary were excluded from the core analytical synthesis. Third, the screened literature was synthesized using conceptual mapping^[20]. Variables were extracted across spatial, temporal, and institutional dimensions to operationalize abstract theoretical concepts into discrete mine planning deliverables, geotechnical prescriptions, and policy proposals.

3.3. Illustrative Case Precedents

To clarify the empirical boundary of this study, the Eden Project (United Kingdom) and the Lusatian Lake District (*Lausitzer Seenland*, Germany) are utilized strictly as *illustrative benchmark precedents* rather than empirical proof or statistical validation. Previous conceptualizations of these sites as "proof of concept" or "empirical validation" overstate their analytical role. As outlined in **Table 3**, both cases represent post-closure landform transformations where heavy extraction had entirely ceased prior to major public redevelopment.

In this study, these precedents serve a specific, bounded function: they demonstrate the physical and institutional feasibility of converting massive open-pit voids and post-industrial topographies into high-value recreational and ecological assets. However, an explicit analytical distinction must be maintained between these post-closure benchmarks and the core proposition of the Integrated Interface Model (IIM). The IIM explores the feasibility of *co-evolutionary parallel processing*, the spatial and temporal alignment of progressive landform design during active extraction. While the Eden Project and Lusatian Lake District illustrate what post-mining topographies can ultimately become, they do not demonstrate simultaneous active heavy haulage, blasting, and public access. Recognizing this limitation ensures that the proposed framework is presented as a prospective policy and design model subject to future empirical, economic, and safety testing.

4. The Integrated Interface Model (IIM)

The **Integrated Interface Model (IIM)** provides a structured conceptual framework for aligning active surface mining operations with progressive post-mining land transformation^[16,17]. Rather than treating mine closure as an abrupt, terminal event occurring near lease expiration, the IIM conceptualizes the active mine lease as a dynamic spatial-temporal interface governed across three interlocking dimensions: Spatial, Temporal, and Institutional^[11,12,17]. By replacing earlier organismic analogies with precise engineering and governance constructs, the model establishes a framework for co-evolutionary planning during active extraction^[16].

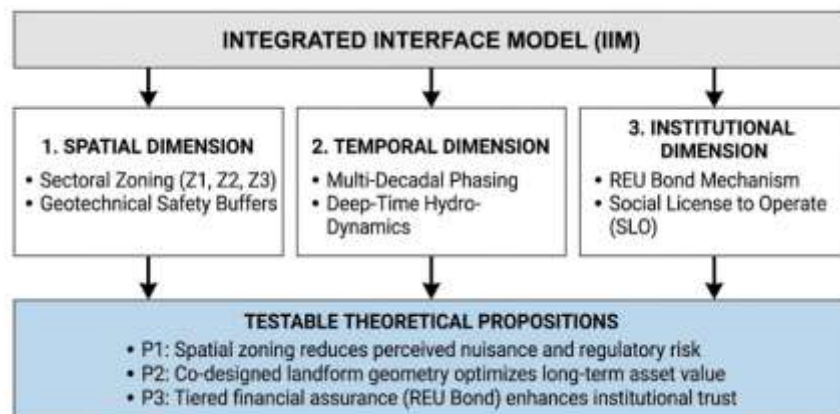


Figure 4. Conceptual architecture of the Integrated Interface Model (IIM), illustrating the interaction between Spatial, Temporal, and Institutional dimensions and their derived testable propositions.

4.1. Spatial Dimension

The spatial architecture of the IIM is built on parallel processing entails the simultaneous execution of industrial mineral extraction and progressive landform preparation within spatially segregated sectors of a single lease^[16,23]. Traditional mine planning segregates extraction and reclamation sequentially across time,

leaving massive pit voids unaddressed for decades^[15,16]. In contrast, parallel processing achieves spatial concurrency by partitioning the active mining lease into three distinct operational zones^[17].

The Active Extraction Zone (Z1) comprises high-intensity industrial sectors dedicated strictly to core extraction activities, including drilling, production blasting, high-wall scaling, and primary heavy haulage, where access is restricted exclusively to authorized mine personnel and machinery operators^[23]. Surrounding this core is the Buffer and Transition Zone (Z2), consisting of intermediate sectors designed to physically and acoustically isolate active extraction from accessible areas^[16]. Zone Z2 incorporates geotechnically engineered physical barriers, blast deflection bunds, acoustic earthen berms, and vegetated corridors that reduce noise, dust, and visual impact^[23]. Finally, the Progressive Public and Ecological Zone (Z3) encompasses de-stressed or completed pit sectors, upper stabilized benches, and backfilled overburden landforms designated for progressive re-vegetation, environmental telemetry monitoring, or controlled public access^[16,17]. By delineating these zones, the IIM eliminates spatial redundancies and resolves site access conflicts, ensuring that progressive land preparation occurs concurrently with resource extraction^[16].

4.2. Geotechnical Safety and Operational Feasibility Constraints

A core constraint of concurrent sectoral zoning is ensuring public safety while high-volume extraction continues in adjacent sectors^[23]. Placing a public-facing zone (Z3) contiguous to an active extraction zone (Z1) requires physical engineering controls, exclusion protocols, and multi-layered risk management rather than reliance on digital monitoring alone^[16,17].

4.2.1. Physical Hazard Isolation and Exclusion Rules

To mitigate flyrock hazards during blasting, minimum physical setback distances of 500 meters are established between active production blasting faces in Z1 and public access points in Z3^[23]. Blasting operations adhere to strict temporal windows during which Z3 is temporarily closed and cleared via automated siren networks and physical access gates^[23]. Benches and access slopes within Z3 undergo geomechanical stabilization prior to public entry, utilizing systematic pattern rock bolting, high-tensile steel wire mesh, catchment ditches, and continuous automated geotechnical tiltmeter monitoring^[23]. Furthermore, heavy haulage routes and light public transit corridors are physically segregated using grade-separated overpasses, dedicated access roads, and continuous 3-meter-high concrete perimeter barriers^[23].

4.2.2. System Redundancy and Risk Management

While Industrial Internet of Things (IIoT) sensors, GPS geofencing, and automated fleet management enhance operational awareness, they cannot serve as standalone safety guarantees^[16,17]. To manage residual risks including sensor latency, physical trespass, power disruptions, or cyber-physical threats, the IIM integrates multi-layered physical defenses^[17]. Hard physical barriers such as concrete berms and continuous perimeter fencing maintain structural separation even if digital geofencing systems fail^[16,17]. Automated interlocking system overrides are engineered to halt heavy equipment within Z1 if a perimeter breach is detected along Z2^[17]. Finally, comprehensive third-party liability insurance frameworks and legal indemnification structures are established prior to granting public access to Z3^[16].

4.3. Temporal Dimension

The temporal dimension extends conventional mine scheduling (typically 10–30 years) to align with deep-time hydrological, geomorphic, and socio-ecological horizons spanning centuries^[15,16]. In standard operational planning, final landform design and water management are deferred until final lease surrender, often resulting in acidic pit lakes, highwall collapse, and long-term municipal liability^[15,17]. The IIM restructures operational schedules into three continuous phases^[16].

During Phase I (Active Extraction & Progressive Geomorphic Shaping), overburden and waste rock stripping are engineered directly into final landforms rather than temporary dumps, establishing initial slope geometries and drainage catchments for Z3 during active extraction^[16,24]. In Phase II (Concurrent Transition & Stabilized Access), upper pit benches and stabilized landforms are opened for educational, scientific, or recreational use while primary extraction continues in deeper pit sectors, supported by continuous telemetry arrays monitoring slope movement, groundwater levels, and water chemistry^[16]. In Phase III (Post-Closure Integration & Deep-Time Stewardship), upon resource depletion, final pit voids transition into long-term regional assets such as hydrodynamic pit lakes, public parks, or renewable energy sites supported by dedicated perpetual maintenance funds^[15,16].

4.4. Institutional Dimension

To bridge the gap between regulatory compliance and long-term land utility, the IIM introduces a policy mechanism termed the Recreational End-Use (REU) Bond^[16,17]. Traditional environmental reclamation bonds focus narrowly on returning mined land to a safe, non-polluting, but ecologically simplified state^[12,17]. The REU Bond operates as a tiered financial assurance instrument, sized explicitly on the capital required to construct stable, public-ready landforms, safe access corridors, and baseline ecological infrastructure^[16]. As the operator achieves progressive stabilization, public access infrastructure, or water quality milestones in Z3 during active mining, a percentage of the financial bond is returned incrementally^[16,25]. Held in a dedicated state-managed escrow account, the bond is legally ring-fenced to ensure that, in the event of corporate insolvency, the accrued funds are protected from general creditors and dedicated exclusively to completing the agreed public landform design rather than reverting to generic site abandonment procedures^[16].

4.5. Formulation of Testable Theoretical Propositions

Rather than presenting unverified outcomes regarding permit timelines, financial return on investment (ROI), or social acceptance as established facts, the IIM structures these relationships as testable theoretical propositions for future empirical evaluation:

- I. **Proposition 1 (P1):** Active surface mines utilizing concurrent sectoral zoning (Z1,Z2,Z3) experience lower public opposition and reduced regulatory delays during lease renewals compared to mines utilizing traditional end-of-life reclamation strategies^[16].
- II. **Proposition 2 (P2):** Integrating final landform geometry directly into active overburden placement schedules lowers total earthmoving costs and increases the post-closure market value of the landform^[16,17].
- III. **Proposition 3 (P3):** Implementing a tiered Recreational End-Use (REU) Bond mechanism increases stakeholder trust and strengthens the operator's Social License to Operate (SLO) across multi-decadal operational lifecycles^[12,16].

Table 4. Core Dimensions and Testable Propositions of the Integrated Interface Model (IIM).

Model Dimension	Operational Subsystem / Governance Component	Key Engineering & Governance Mechanisms	Derived Testable Theoretical Proposition	Author Citations
Spatial Dimension	Sectoral Zoning (Z1,Z2,Z3) & Physical Hazard Isolation	Flyrock setbacks (>500 m), rockfall mesh, grade-separated haulage, physical perimeter barriers	P1: Concurrent spatial zoning reduces regulatory risk and community conflict during operational life	[16]; [17]; [23]

Temporal Dimension	Multi-Decadal Phasing & Geomorphic Landform Design	Progressive overburden placement, continuous slope stabilization, automated water monitoring	P2: Progressive landform shaping during active mining lowers total closure costs and enhances post-mining land value	[11]; [15]; [16]; [24]
Institutional Dimension	Recreational End-Use (REU) Bond & Multi-Stakeholder Governance	Tiered bond credit release, escrow insolvency protection, co-managed land-use agreements	P3: Structured REU financial assurance builds institutional trust and secures long-term Social License to Operate	[12]; [17]; [25]

Table 4. (Continued)

5. Discussion and Synthesis

The Integrated Interface Model (IIM) transitions mine closure planning from descriptive, end-of-life remediation toward a structured, predictive framework for multi-decadal landscape stewardship. By synthesizing Social-Ecological Systems (SES) governance with geotechnical engineering and landscape scale theory, the framework establishes a logic chain for evaluating how open-pit mining leases can be governed concurrently across active extraction and progressive land transformation. Rather than presenting unverified operational returns or guaranteed approvals as established facts, the IIM operationalizes these relationships into three core testable propositions (*P1, P2, P3*), detailed in **Table 5**.

Table 5. Core Conceptual Propositions, Theoretical Drivers, and Testable Outcomes.

Proposition	Core Theoretical Drivers	Governance & Engineering Mechanisms	Testable Theoretical Outcome / Hypothesis	Author
<i>P1:</i> Concurrent Sectoral Zoning	SES Governance; Spatial Parallel Processing	Sectoral Zoning (Z1,Z2,Z3); Concurrent Permitting Protocols	Hypothesis: Lower community opposition, reduced litigation risk, and shortened lease renewal timelines.	[11]; [22]; [26]; [27]
<i>P2:</i> Progressive Landform Engineering	Industrial Sublime Geomorphic Topography	Active Overburden Shaping; Geotechnical Bench Stabilization	Hypothesis: Reduced net earthmoving costs and increased long-term post-closure asset valuation.	[8]; [13]; [14]; [28]; [29]
<i>P3:</i> REU Bond Mechanism	Financial Assurance Theory; Institutional Risk Sharing	Tiered Financial Escrow; Ring-Fenced Credit Release	Hypothesis: Enhanced institutional trust and sustained Social License to Operate (SLO).	[30]; [31]; [32]

5.1. Proposition 1: Concurrent Sectoral Zoning as a Mitigant for Social Risk and Regulatory Delay

Traditional surface mining governance often suffers from regulatory delays and permitting stagnation, frequently termed "permit lag", arising from local opposition, environmental litigation, and uncertainty regarding post-closure land utility^[27]. This friction typically stems from stakeholder perceptions of active mining as an exclusively extractive event that generates immediate local nuisances while deferring site remediation to a distant, uncertain future^[22,26]. By implementing concurrent sectoral zoning, the spatial and temporal core of the IIM operators integrate progressive landform preparation into active operational schedules (Section 4.1). When a mine operating plan establishes Z3 (Progressive Public and Ecological

Zone) sectors alongside active extraction in Z1, the lease functions as an evolving landform transformation project rather than a closed industrial site. Recent studies in industrial ecology indicate that early-stage social infrastructure, transparent site access, and visible environmental stewardship reduce community opposition and streamline regulatory reviews^[22,26]. Therefore, Proposition 1 posits that concurrent spatial planning transforms active leases from inaccessible industrial voids into structured multi-use landscapes, significantly lowering regulatory and legal friction during operational lifecycles (P1).

5.2. Proposition 2: Co-Designed High-Intensity Landforms and Passive Reclamation

The default regulatory standard for mine reclamation historically centers on passive green space, typically involving overburden capping, re-grading, and basic re-vegetation^[7]. While geotechnically stable and non-polluting, passive reclamation often yields low long-term economic return for host communities while requiring continuous maintenance expenditure to prevent land degradation^[33]. Proposition 2 argues that intentionally engineering pit topographies for high-intensity re-use such as rock climbing, deep-water diving, or regional trail networks leverages the steep vertical scale and unique geometry of open-pit voids as economic assets^[8].

The extreme physical scale of open-pit mines represents a rare geomorphic feature that is exceptionally difficult to replicate artificially. Modern landscape architecture increasingly recognizes these monumental landforms as opportunities for specialized regional tourism and recreational infrastructure^[28]. Integrating these final geometric requirements into active overburden placement and bench stabilization schedules (Section 4.1) reduces long-term re-handling expenses. High-intensity end-uses support higher user fees, local commercial retail, and persistent regional tourism that passive grass caps cannot sustain^[29]. Consequently, co-designing landform geometry during active mining establishes a more resilient post-mining economic base, converting potential long-term liabilities into regional economic assets (P2)^[34].

5.3. Proposition 3: The Recreational End-Use (REU) Bond as an Institutional SLO Catalyst

An operator's Social License to Operate (SLO) depends heavily on institutional trust, which remains vulnerable to historical industry patterns of premature closure or site abandonment^[30]. Proposition 3 posits that the Recreational End-Use (REU) Bond (Section 4.4) serves as a structured financial mechanism to align corporate incentives with long-term community trust. Under traditional financial assurance systems, communities bear the long-term risk of site abandonment or corporate insolvency, facing the prospect of unfinished reclamation^[35]. The REU Bond restructures this risk profile by legally ring-fencing capital specifically for public-ready infrastructure and progressive ecological stabilization. This mechanism aligns with contemporary Sustainability-Linked Bonds and Social Impact Instruments, which connect financial performance to verified social and environmental milestones^[31]. Furthermore, granting controlled, safe public access to stabilized Z3 sectors during active extraction provide tangible proof of progress. Providing early access and visible progress helps offset localized operational nuisances (e.g., dust, noise, traffic) by delivering concurrent public benefits^[32]. This financial and physical commitment transforms mine closure from an unverified future promise into an active, co-managed institutional agreement (P3).

5.4. Limitations and Boundaries of the Conceptual Model

While the IIM provides a comprehensive framework, several operational, geotechnical, and institutional limitations must be acknowledged:

I. **Geotechnical and Safety Constraints:** Operating public-facing sectors (Z3) contiguous to active extraction (Z1) presents significant geotechnical and blast hazard challenges. Maintaining flyrock exclusion

setbacks ($> 500m$), rockfall catchment systems, and continuous tiltmeter monitoring is required to prevent accidental injury.

II. **Technological Redundancy:** Digital safety systems including IIoT monitoring, GPS geofencing, and automated fleet overrides enhance situational awareness but cannot serve as standalone safety guarantees. Multi-layered physical barriers, grade-separated transit routes, and clear legal indemnification structures remain mandatory.

III. **Regulatory and Statutory Adaptation:** Implementing tiered financial assurance mechanisms like the REU Bond requires legislative updates in mine safety and financial assurance codes across different jurisdictions. Regulators must establish standardized verification protocols before issuing incremental bond releases.

5.5. Agenda for Future Research

Since this manuscript establishes a conceptual theory-building synthesis, empirical validation of propositions $P1$, $P2$ and $P3$ represents the primary direction for future research:

A. **Empirical Testing of $P1$:** Comparative policy analyses across mining jurisdictions to quantify the impact of progressive sectoral zoning on permitting approval timelines and public litigation rates.

B. **Geotechnical & Blast Modeling:** 3D numerical blast simulation and rockfall trajectory modeling to refine physical setback dimensions ($Z2$) under varying geological conditions.

C. **Micro-Economic Modeling ($P2$):** Cost-benefit evaluations comparing the net present value (NPV) of progressive landform shaping against traditional end-of-life earthmoving.

D. **Financial Assurance Analysis ($P3$):** Legal and financial modeling to evaluate the solvency protection and statutory feasibility of REU Bonds within national mining codes.

6. Structural and Institutional Challenges

While the Integrated Interface Model (IIM) provides a structured framework for progressive landform co-design, its practical implementation faces distinct geotechnical, statutory, and environmental friction points^[17,23]. Moving beyond the theoretical propositions ($P1$ – $P3$) established in Section 5 requires confronting three operational challenges: physical hazard isolation, legacy statutory inertia, and the risk of aesthetic features obscuring environmental liabilities^[12,15,27] (**Table 6**).

Table 6. Critical Operational Paradoxes, Technical Constraints, and Propositional Alignments.

Critical Challenge / Paradox	Operational & Structural Risk	Integrated Engineering & Policy Mechanisms	Derived Theoretical Proposition Alignment	Author Citations
Safety vs. Public Access	Industrial blast/haulage hazards vs. public access contiguous to active sectors.	Physical setback zones ($>500m$), rockfall mesh, grade-separated transit routes, IIoT sensor redundancies.	$P1$: Concurrent sectoral zoning maintains safety while reducing lease friction.	[17]; [23]
Legacy Codes vs. Innovation	19th-century single-use legislation prohibiting multi-use active leases.	Tiered Recreational End-Use (REU) Bonds; statutory multi-use zoning policy frameworks.	$P3$: Structured REU financial assurance bridges legal gaps and builds institutional trust.	[16]; [27]

Aesthetics vs. Ecological Compliance	Post-industrial landscape design obscuring ongoing environmental contamination.	Strict prioritization of SES environmental compliance over recreational infrastructure.	P₂ : Progressive landform [12]; [15] shaping must fulfill baseline ecological criteria before public re- use.
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Table 6. (Continued)

6.1. The Safety-Access Dilemma: Physical Exclusion and Hazard Isolation

The co-location of active extraction zones (Z1) alongside public-facing sectors (Z3) creates a fundamental operational tension between maintaining public access and ensuring industrial safety^[16,23]. Traditionally, mining governance has addressed this tension by imposing total exclusion from leased areas, thereby prioritising operational security over opportunities for public use^[26]. However, within the IIM, managing public proximity requires a more integrated approach in which access arrangements are determined by geomechanical conditions, physical separation and effective structural containment^[17,23]. This approach does not diminish the importance of established safety requirements; rather, it makes them central to the design and operation of multifunctional mining landscapes. Mandatory physical controls should therefore include minimum 500-metre blast setback radii, systematic pattern rock bolting, catch ditches and grade-separated haulage corridors^[23]. Although digital technologies, including Industrial Internet of Things (IIoT) sensor arrays, GPS geofencing and automated fleet controls, can strengthen monitoring and operational coordination, they must function as supplementary safeguards rather than substitutes for physical protection^[16,17]. This distinction is critical because sensor latency, cyber-physical disruptions and unauthorised entry may compromise the reliability of digital systems. Consequently, hard perimeter barriers, automated machinery interlocks and formal legal indemnification structures must be established before public access to Z3 is permitted^[17,23]. The central challenge is therefore not simply to facilitate access to active mining landscapes, but to ensure that such access remains subordinate to demonstrable safety conditions.

6.2. The Regulatory Gap: Legacy Legislation and Institutional Inertia

Even where physical safeguards make multifunctional zoning technically feasible, its implementation may be constrained by legacy statutory frameworks and institutional resistance to alternative approaches to mine-land management^[22,27]. In several mining jurisdictions, legislation remains rooted in single-use principles. For example, the U.S. General Mining Act of 1872 emerged from a framework that prioritised mineral extraction, while conventional reclamation requirements have often emphasised restoring disturbed land to an approximate original contour or a basic agricultural condition following the surrender of a lease^[22,27]. Such requirements can create regulatory friction when engineered landforms, including rock-climbing walls, stabilised pit amphitheatres and diving voids, are proposed as components of post-mining landscapes. Rather than being recognised as potentially valuable recreational assets, these features may be treated by permitting authorities as unreclaimed liabilities requiring further intervention^[22]. Overcoming this institutional inertia therefore requires statutory frameworks that explicitly accommodate multi-use active zoning and provide a formal basis for instruments such as the REU Bond^[16,27]. However, regulatory reform alone is insufficient. Operators must also provide robust geomechanical assessments and financial evidence demonstrating that co-designed landforms can maintain long-term slope stability and environmental safety at levels equivalent to or better than those achieved through conventional backfilling^[17,23]. In this respect, the viability of the IIM depends on aligning regulatory recognition of multifunctional land use with independently verifiable engineering performance and enforceable financial responsibility.

6.3. Environmental Compliance and the Risk of Aesthetic Masking

Beyond operational safety and regulatory barriers, the IIM faces a further governance challenge such as the possibility that landscape design and recreational development could create an appearance of successful rehabilitation while concealing unresolved environmental liabilities, including active acid mine drainage (AMD) and heavy-metal leaching from overburden waste dumps^[12,26]. This risk is particularly significant because visually attractive landforms and accessible recreational spaces do not, in themselves, demonstrate that the underlying environment is safe. Accordingly, the scientific integrity of the IIM depends on ensuring that baseline Social-Ecological System (SES) parameters take precedence over aesthetic objectives and recreational programming^[11,12]. Environmental compliance indicators, including groundwater quality, tailings geochemical stability and soil toxicity, must therefore remain non-negotiable conditions for development and public access^[17,26]. Recreational infrastructure must neither circumvent established environmental standards nor provide a justification for postponing remediation or transferring long-term liabilities to future land managers^[16]. As Morton^[15] observes, the environmental consequences of industrial activity can persist over multiple decades, irrespective of how restored landscapes appear at the surface. Consequently, progressive landform engineering should be designed not merely to accommodate recreational use but also to support the financing, monitoring and acceleration of site remediation. This requires waste streams and contaminated materials to be managed with the same engineering rigour applied to mineral extraction, ensuring that recreational value is developed alongside, and never at the expense of, measurable environmental recovery^[12,17].

7. Conclusion

The transition from conventional end-of-life reclamation toward proactive mine transition requires moving beyond the rigid sequential paradigms that historically defined surface mining governance. Open-pit mineral extraction creates multi-decadal landscape topographies that function as enduring features within local socio-ecological systems. By synthesizing Social-Ecological Systems governance with geotechnical engineering and landscape scale theory, the Integrated Interface Model provides a structured framework for managing this multi-decadal footprint across three interlocking dimensions: Spatial, Temporal, and Institutional. The core analytical contribution of this research lies in establishing a non-metaphorical framework for evaluating progressive landform co-design during active mineral extraction. Through spatial parallel processing, deep-time multi-decadal phasing, and structured financial assurance mechanisms via the Recreational End-Use Bond, the model reconciles active mineral extraction with progressive landform preparation. By translating these structural mechanisms into testable theoretical propositions (P1, P2, and P3), the model provides a foundation for future empirical research evaluating regulatory friction, landform valuation, and institutional trust without relying on unverified claims of immediate operational returns.

Advancing progressive mine landform integration therefore requires aligning engineering practices, regulatory frameworks, and financial assurance instruments. Updating single-use statutory codes to accommodate adaptive multi-use zoning enables operators and regulatory authorities to evaluate post-mining voids as structured regional assets rather than deferred liabilities. When baseline environmental compliance, geotechnical safety, and chemical containment strictly precede site re-use, co-designed surface mines can successfully transition from active mineral production toward long-term, multi-functional land utility.

Conflict of Interest

The authors declare no conflicts of interest.

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