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Extending digital simulation frameworks from energy and manufacturing transitions to mine closure: a Decent Work perspective

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Abstract

Mine closure imposes severe socio-economic impacts on mining-dependent communities – sudden unemployment, service collapse, and population decline – yet closure planning still relies largely on static, qualitative assessment. Digital simulation methods such as agent-based modelling (ABM) and digital twins have been applied to socio-economic transitions in energy and manufacturing. Still, no published study applies them to the socio-economic dimensions of mine closure. This paper asks whether such methods could be adapted to that context. Through a structured narrative review, it distinguishes between modelling approaches that are frequently conflated – agent-based models, system dynamics, and digital twins – and maps their capabilities against documented closure challenges using the International Labour Organisation's Decent Work framework. On this basis, it proposes, as a research design rather than a validated model, a participatory agent-based simulation for closure: an ABM of workforce and community transition, optionally linked to a social digital twin, with stakeholder participation operationalising the social dialogue pillar. The paper sets out what would be required to assess the design and argues that its value depends on transparent data sharing between operators and communities.

Keywords: *mine closure, digital simulation, agent-based modelling, digital twins, just transition, Decent Work, energy transition, Industry 5.0, workforce displacement, community resilience*

1 Introduction

Mine closure is one of the most disruptive industrial transitions a community can face. For remote, mining-dependent towns, the end of operations can trigger sudden unemployment, the collapse of mine-provided services, population decline and the erosion of community identity (Edwards et al. 2019; Warhurst et al. 2024). Inadequately addressed social needs in planning frameworks (Edwards et al. 2019) are further complicated by fragmented and overlapping regulatory requirements and by poor whole-of-life cycle approaches to the social aspects of closure (Unger et al. 2025), making planning for such events challenging – or, as Rittel & Webber (1973) termed it, a 'wicked' planning problem. While traditional mine closure frameworks remain constrained by technical compliance and static checklists, modern industrial transitions are increasingly governed by the paradigm of Industry 5.0.

> *'Industry 5.0 is characterized by going beyond producing goods and services for profit. It places the worker at the centre of the production process and uses new technologies to provide prosperity beyond jobs and growth while respecting the production limits of the planet. It complements the existing Industry 4.0 approach by specifically putting research and innovation at the service of the transition to a sustainable, human-centric, and resilient industry' (Breque et al. 2021).*

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Although there has been a change in thinking toward integrating social dimensions into decommissioning frameworks, regulatory planning mechanisms and localised socio-economic realities often hinder meaningful community inclusion (Bainton & Holcombe 2018). Post-mining land use is often treated as a retrospective checklist rather than as an adaptive, community-driven vision established at the onset of operations. When mining companies prioritise technical or environmental compliance metrics over collaborative social provisioning, authentic participation and innovation are stifled, long-term operator-community relationships are adversely affected, and the company's social licence to operate is eroded (Kozłowska-Woszczycka & Pactwa 2022).

A significant barrier to effective post-mine land use analysis is the spatial fracture of modern mining workforces. Traditional transition models assume a geographically stationary community (Blackwell & Dollery 2017); however, modern resource regions rely heavily on fly-in, fly-out (FIFO) workforces (House of Representatives Committees 2013; OECD 2020). This creates asymmetric social and economic tipping points, dividing stakeholders into local residential agents – bound to post-closure infrastructure (Edwards et al. 2019; Warhurst et al. 2024) – and transient FIFO agents, whose economic behaviours and re-employment horizons exist beyond the host community (Perry & Rowe 2015). To build an equitable participatory framework, simulation methods must dynamically capture the division of social networks (Campfens et al. 2025; Dray et al. 2007).

This paper addresses three research questions: (1) Which simulation methods have been applied to socio-economic aspects in energy and manufacturing transitions, and what does each model? (2) Which of these capabilities correspond to documented mine closure challenges, and where do mining contexts require methodological adaptation? (3) What would a participatory, Decent Work-oriented simulation design for closure entail, and what is required to assess its transferability?

2 Methodology

The methodology for constructing the integrated socio-technical framework presented in this study employs a dual-layered research design that combines a scoping review with rigorous conceptual analysis. Given that the socio-economic challenges of industrial downscaling and post-mine land use extend beyond traditional engineering parameters, a transdisciplinary approach is required to map the relevant landscape.

A scoping review was selected as the primary mechanism to systematically map literature across distinct, disparate fields–ranging from regional development and environmental governance to computer-assisted simulation architectures. This methodology enabled the identification of structural gaps in current project management protocols, specifically regarding the non-linear dynamics of stakeholder participation and the persistent misalignment between regulatory compliance and community inclusion.

After the literature mapping phase, a conceptual analysis was conducted to dissect, clarify, and reassemble core tenets from these distinct domains. Instead of simply aggregating existing literature, this analysis isolates the variable mechanics of spatial mismatch, social network tipping points, and multi-agent systems, thereby providing the analytical foundation necessary to develop the integrated agent-based model (ABM) and social digital twin (SDT) framework.

2.1 Literature sourcing strategy and database parameters

To compile a robust, multi-domain literature matrix, data collection was executed across three primary digital platforms, allowing for a comprehensive capture of peer-reviewed engineering, sociological, and economic research:

- Google Scholar: Utilised to map the broader citation landscape, identify foundational highly cited papers, and trace emerging 2025/2026 academic literature regarding social tipping points, place-based decarbonisation mismatches, and just transition frameworks.

- SciSpace: Deployed as an AI-augmented literature exploration tool to accelerate cross-disciplinary data extraction, analyse conceptual linkages across disparate fields, and synthesise technical parameters from complex system dynamics and multi-agent models.
- Curtin University Online Library: Used to execute deep database queries across high-impact indexing platforms (including Scopus, Web of Science, and IEEE Xplore) and to access localised Australian resource sector data, regional development reports, and specialised mine closure proceedings (e.g. Australian Centre for Geomechanics repository).

Keyword strings were combined using Boolean operators (AND/OR) to isolate three core pillars of inquiry:

1. Mining/Energy Transitions: ('mine closure' OR 'energy transition' OR 'industrial downscaling' AND 'just transition')
2. Social Dynamics: ('social license to operate' OR 'participation' OR 'anticipatory decline' OR 'community resilience')
3. Simulation Architecture: ('agent-based model' OR 'system dynamics' OR 'social digital twin')

The final phase of the research methodology involved translating the synthesised literature to inform the development of the conceptual frameworks put forward.

3 Simulation models review

Socio-economic transitions are complex, non-linear processes that involve the co-evolution of technology, human behaviour, regulatory institutions, and physical infrastructure. Our scoping review analysed three primary simulation paradigms: ABM, system dynamics (SD), and SDTs. Each operates differently, as summarised in Table 1, with expanded descriptions.

Table 1 Review of digital models

Systemic scale	**Micro to meso: represents individual agent states and localised interactions**	**Macro: represents aggregate accumulation processes and feedback structures**	**Multi-scale: integrates physical assets, geo-individuals, and macro-societal layers**
Causal direction	Bottom-up: global patterns emerge from local interaction heuristics	Top-down: causal structure of feedback loops dictates system behaviour over time	Bidirectional: real-time, continuous coupling between the physical and virtual systems
Mathematical basis	Conditional state transition logic, rule-based heuristics, genetic algorithms, Tabu search	Systems of non-linear ordinary differential equations (dx/dt)	Real-time multi-agent engines, RAG-augmented LLMs, BIM/GIS databases
Key capability	Generates emergent phenomena, path dependency, and spatial-stochastic behaviours	Simplifies feedback mechanisms, policy delays, and long-term systemic stability	Enables high-fidelity 'what-if' policy testing, real-time sensing, and dynamic visualisation
Primary limitation	High computational overhead, demanding parameterisation, and low mathematical tractability	Incapable of representing individual heterogeneity or spatial topology	High data-ingestion requirements, privacy concerns, model bias, and risks of false precision

Note: BIM = building information modelling; GIS = geographic information systems; LLM = large language model; RAG = retrieval-augmented generation

3.1 Agent-based modelling

ABM is a bottom-up, micro-scale computational methodology that represents social systems through their constituent autonomous, heterogeneous parts, termed 'agents' (Squazzoni 2012; Edmonds & Meyer 2017). These agents, representing individual citizens, workers, households, or firms, execute localised decision-making heuristics and interact within spatially and socially embedded environments (Schulze et al. 2017).

Ontologically, ABMs reject perfect rationality and system-level equilibrium. Instead, they focus on how macroscopic social phenomena – such as labour market bottlenecks, geographic segregation, or the formation of political polarisation – emerge dynamically from microscopic interaction rules (Squazzoni 2012; Campfens et al. 2025). This bottom-up logic is highly effective at capturing path dependency, stochastic variations, and spatial constraints (Schulze et al. 2017).

At the psychological level, ABMs can integrate cognitively realistic architectures, such as the Agent Zero framework, which models agents with distinct affective, deliberative, and social network modules to simulate adaptive behavioural changes under stress or risk (Campfens et al. 2025). To resolve complex scheduling and logistics problems, ABMs can incorporate metaheuristic optimisation algorithms, such as genetic algorithms or Tabu search (Valinejad et al. 2022). However, ABMs present challenges in parameterisation and analytical tractability; high-dimensional parameter spaces often lead to computational bottlenecks, making it difficult to isolate specific causal pathways or prove system-level stability (David et al. 2017; Schulze et al. 2017).

3.2 System dynamics

SD is a top-down, macro-scale modelling paradigm designed to study the behaviour of complex systems over time through feedback loops, accumulations, and time delays. Developed by Jay W. Forrester, SD conceptualises systems through mathematical feedback structures in which individual actors' agency is aggregated into continuous state variables (Hovmand 2014). The structural foundation of an SD model consists of causal loop diagrams for qualitative mapping and stock-and-flow diagrams for mathematical formulation

The primary strength of SD lies in its ability to clarify how a system's internal feedback structure generates its aggregate behaviour over time, such as oscillations, exponential growth, or asymptotic stability (Hovmand 2014). In transition studies, SD is widely used to evaluate macro-level policy interventions, such as circular economy transitions or regional labour restructuring (García-García et al. 2024; Hesketh et al. 2024). However, because SD relies on aggregate, homogeneous stocks, it cannot capture individual-agent heterogeneity, spatial topology, or localised social network interactions (Squazzoni 2012; Schulze et al. 2017).

3.3 Social digital twins

SDTs represent an emerging class of simulation technology that bridges the divide between physical assets, institutional rules, and the lived experiences of human populations (Fujitsu Global 2025; Carnegie Mellon University 2022). While conventional urban digital twins focus on physical systems, such as electricity grids, building structures, or traffic networks (Grieves & Vickers 2016; Mohanraj & Balaji 2026), SDTs explicitly integrate a dynamic social layer (Dhakal et al. 2026). The SDT paradigm mirrors physical and social systems ('parallel societies') in a virtual environment with automated, bidirectional, real-time reviewers' addressing. Architecturally, SDTs follow a three-stage life cycle: conceptualisation, modelling, and application (Dhakal et al. 2026). To build detailed representations of individuals (geo-individuals) and community networks (geo-socials), SDTs ingest real-time and administrative data to function as interactive 'sandboxes' where policymakers can simulate dynamic, multi-system policies (Fujitsu Global 2025; Okimi 2025). SDTs must navigate structural limitations, including data privacy issues, model bias, opacity, and the conceptual risk of 'false precision', in which overreliance on a high-resolution simulation can lead to unwarranted confidence in specific policy outcomes (Deutsch et al. 2024; Mohanraj & Balaji 2026).

4 Discussion of existing applications

Energy transition simulations show robust capabilities for modelling workforce displacement, community adaptation, and regional policy interventions. Crucially, García-García et al. (2024) developed a macro-level SD model for Spanish -mining areas, establishing a precedent for using macro-level feedback loops to simulate structural transitions and map systemic delays in policy absorption. Tracking 15,000 workers across mining, renewable energy, and alternative sectors, their simulation reveals that without initiative-taking policy intervention, local unemployment peaks at 28% within five years of closure, triggering a population decline exceeding 15% and the collapse of local services.

Furthermore, the Spanish model explicitly operationalises the ILO Decent Work pillars:

- Employment creation: modelled via renewable energy job creation rates, entrepreneurship support, and investments in regional economic diversification.
- Rights at work: reflected in alternative wage differentials, revealing that renewable energy jobs pay 15–20% less than mining jobs, thereby necessitating wage subsidies to maintain income security. (Employment trends in mining and the renewable energy sector, 2023).
- Social protection: modelled through the duration of unemployment insurance, early retirement eligibility, and pension bridging for workers aged fifty-five and over.
- Social dialogue: operationalised through participatory scenario workshops where workers and community members actively co-design transition pathways and evaluate policy trade-offs.

Regional transition literature strongly supports the use of advanced simulation architectures to address structural downscaling. Analysing Poland's phase-out, Martin & Broughel (2025) highlight a critical limitation in static assessments: their inability to capture fine-grained, emergent household choices. Their empirical findings on regional demographics and structural resistance in the Silesia region strongly justify the need for active ABM to map these non-linear human behaviours.

Furthermore, participatory modelling is key to the success of transition simulation. Harrahill & Douglas (2019) demonstrate that engaging workers, unions, employers, and local governments throughout model development builds trust and integrates local knowledge. This collaborative approach operationalises social dialogue, uncovering community priorities that technical experts often overlook, such as preserving social cohesion, maintaining local identity, and ensuring intergenerational equity.

Finally, energy transition simulations show the power of scenario analysis for policy testing. Krawchenko & Gordon (2022) compare scenarios for oil and gas regions, revealing that integrated policy packages – combining income support, workforce development, and place-based investment – reduce regional unemployment by 40% and population decline by 60% compared to minimal interventions (*Unlocking Opportunity: A Global Framework for Enabling Transitions to the Jobs of Tomorrow*). Crucially, their work identifies policy timing as decisive: interventions launched 3–5 years before closure are vastly more effective than reactive, post-closure measures (Gagen et al. 2024).

4.1 Evidence from Industry 5.0 manufacturing simulations

Industry 5.0 frameworks pioneer simulation paradigms that integrate operational milestones with workforce transition planning. Structurally, Lehmann et al. (2023) introduce the internet of digital twins framework, demonstrating a conceptual symbiosis between autonomous agent models and twin environments. While initially designed for manufacturing flexibility, this multi-scale architecture provides a valuable blueprint for linking localised community simulations directly to rigid operational closure timelines. By dynamically updating with real-time tracking data, these frameworks allow adaptive management as local conditions evolve.

To operationalise these agent behaviours, Woźniak et al. (2025) establish a foundational baseline for skill-based transitions by defining a Sectoral Qualifications Framework for the copper industry. By mapping standardised green and digital competencies across distinct labour tiers, their framework provides the explicit taxonomy required to program agent skill profiles and training intervention rules within an interactive simulation sandbox.

Furthermore, SDTs enhance social protection through predictive analytics, providing lead time to minimise socio-economic shocks. For extractive environments, Cranford (2023) proposes linking operational schedules directly to ESG targets and workforce welfare metrics. This allows continuous monitoring of community wellbeing, early identification of systemic vulnerabilities, and adaptive policy adjustments. This multi-scale coupling is uniquely suited to mine closure challenges, building on the architecture outlined by Lehmann et al. (2023). It models how a single operational shutdown cascades through localised supply chains – capturing downstream processing, regional transportation, and service industry vulnerabilities that single-scale assessments overlook.

Finally, these interactive simulations democratise social dialogue. By using intuitive interfaces, non-technical stakeholders can actively explore alternative land use scenarios, visualise long-term outcomes, and negotiate policy trade-offs. Manufacturing and extractive precedents demonstrate that these digital platforms serve as effective boundary objects, facilitating authentic communication and transparent negotiation among diverse groups with competing regional interests.

4.2 Transferability to mine closure contexts

The structural similarities between energy transitions, manufacturing restructuring, and mine closure create strong conditions for methodological transfer. All three contexts involve economic dependence on a single industry, geographically concentrated impacts, workforce displacement, and challenges to community resilience (Blackwell & Dollery 2017; Warhurst et al. 2024). Energy transition simulations address -dependent regions facing a decarbonisation scenario directly analogous to mining regions facing ore depletion or market collapse. Manufacturing simulations address plant closures in specialised industrial regions – again, closely paralleling mining-town dynamics (Lehmann et al. 2023).

However, mine closure contexts pose distinctive challenges that require methodological adaptation. Mining communities tend to be more geographically isolated than or manufacturing regions, which limits access to employment alternatives, retraining, and social services (Blackwell & Dollery 2017). Simulations must therefore explicitly incorporate spatial constraints, including transportation costs, service accessibility, and migration barriers. Additionally, mining workforces often have specialised skills with limited transferability, necessitating more intensive retraining than in or manufacturing sectors (Strachan et al. 2016). Accordingly, simulations must account for longer training durations, greater program costs, and lower success rates.

Mining operations often supply comprehensive infrastructure – housing, healthcare, education, and utilities – that collapses at closure, creating dependencies absent from most and manufacturing contexts (Edwards et al. 2019). Simulations should model this transition, including the costs of transferring services and the effects of service degradation on community viability. Furthermore, resource-dependent peripheral regions often experience substantial resource-rent leakage to central treasuries alongside constrained local administrative bandwidth, limiting the scope of autonomous municipal policy interventions (Saha et al. 2023). Consequently, regional simulations should incorporate realistic subnational fiscal boundaries and institutional capacity limits rather than assuming frictionless or unconstrained public resources.

Despite these structural challenges, the core methodological capabilities of energy and manufacturing simulations transfer effectively to mine closure. Multi-agent systems provide an essential framework for navigating regional transitions in which corporate-community power asymmetries are pronounced. While computational tools map emergent actions, qualitative transition research highlights the friction that occurs when planning fails to achieve collaborative alignment. For example, empirical work by Nicola & Schmitz (2022) on European phase-outs demonstrates that highly discordant stakeholder agendas, localised communication gaps, and systemic institutional mistrust can critically stall regional transition pathways before physical closure. Incorporating these behavioural friction variables directly into the simulation parameters prevents the optimisation of unrealistic transition timelines. The Decent Work framework offers a consistent evaluative lens across all three contexts, guiding simulations to address employment creation, rights at work, social protection, and social dialogue (ILO 2022). Energy and manufacturing precedents show these pillars can be operationalised through features such as modelling alternative employment pathways, wage dynamics, social safety nets, and participatory processes (García-García et al. 2024; Lehmann et al. 2023). These capabilities transfer directly to mine closure simulation, providing a blueprint for Decent Work integration.

Empirical validation in energy and manufacturing contexts strengthens the case for mine closure applications. Energy transition simulations have demonstrated accuracy in forecasting unemployment, migration, and service impacts, with ex-post evaluations confirming model predictions within 10–15% margins, as documented by Martin & Broughel (2025). Concurrently, manufacturing digital twin architectures have proven effective for anticipating workforce displacement and evaluating the long-term efficacy of regional retraining programs, a capability established by Lehmann et al. (2023) and expanded by Long et al. (2025). This empirical history suggests that adapted socio-technical simulations may provide reliable decision support for mine closure planning, reducing institutional reliance on purely qualitative assessments and static economic impact studies (Warhurst et al. 2024).

Building on precedents in energy and manufacturing, this paper proposes an integrated digital simulation framework for mine closure planning that operationalises Decent Work principles. The framework, as shown in Table 2, combines agent-based modelling for community-level dynamics with digital twin capabilities for operational planning and real-time monitoring. This hybrid architecture enables multi-scale simulation, capturing individual worker decisions, household responses, firm behaviour, and regional economic trajectories while maintaining linkages to mine operational planning (Lehmann et al. 2023; García-García et al. 2024). The proposed framework consists of four interconnected modules visualised in Figure 1.

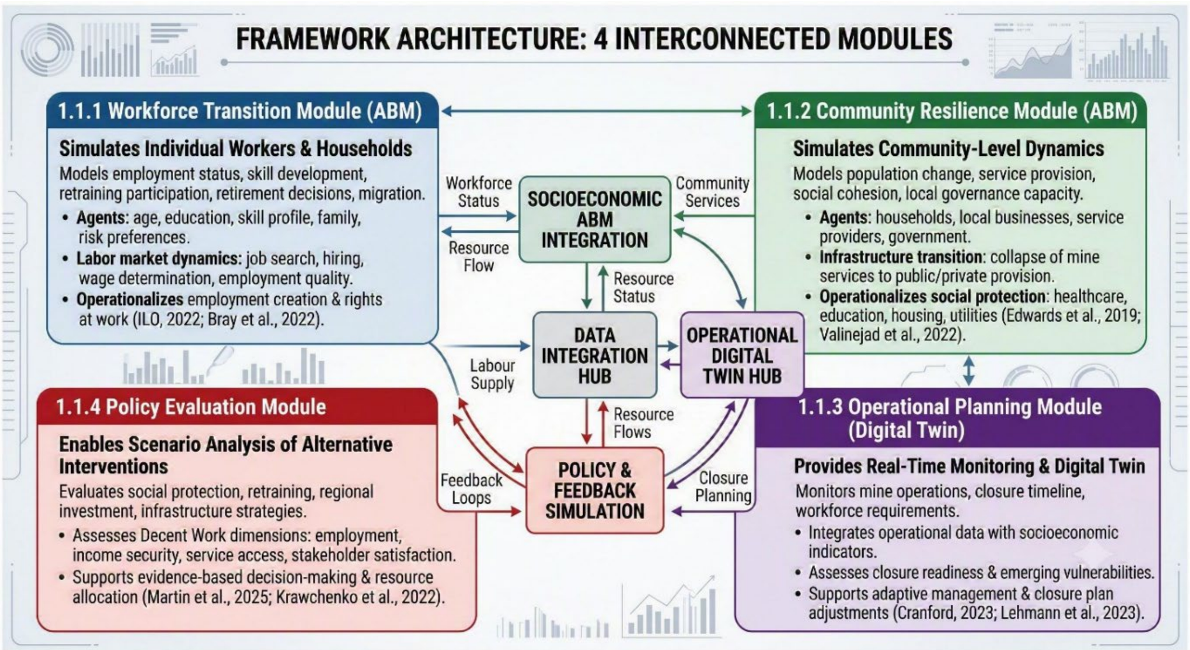

Figure 1 Visualised framework

4.3 Workforce transition module (ABM)

Simulates individual workers and households, modelling employment status, skill development, participation in retraining programs, retirement decisions, and migration. Agents are heterogeneous in age, education, skill profile, family circumstances, and risk preferences. The module captures labour market dynamics, including job search, hiring, wage determination, and employment quality. This module operationalises employment creation and rights at work pillars by modelling alternative livelihood pathways and employment standards (ILO 2022; Bray et al. 2022).

4.3.1 Community resilience module (ABM)

Simulates community-level dynamics, including population change, service provision, social cohesion, and local governance capacity. Agents include households, local businesses, service providers, and government entities. The module models infrastructure transition, capturing the collapse of mine-provided services and the shift to public or private provision. This module operationalises social protection by modelling access to healthcare, education, housing, and utilities throughout the transition (Edwards et al. 2019; Valinejad et al. 2022).

4.3.2 Operational planning module (digital twin)

Provides real-time monitoring of mine operations, closure timeline, and workforce requirements. The digital twin integrates operational data with socio-economic indicators, enabling continuous assessment of closure readiness and early warning of emerging vulnerabilities. This module supports adaptive management, allowing closure plans to adjust as conditions evolve (Cranford 2023; Lehmann et al. 2023).

4.3.3 Policy evaluation module

Enables scenario analysis of alternative policy interventions, including social protection programs, retraining initiatives, regional investment, and infrastructure transition strategies. The module evaluates policy effectiveness across Decent Work dimensions, assessing employment outcomes, income security, service access, and stakeholder satisfaction. This module supports evidence-based decision-making and resource allocation (Martin & Broughel 2025; Krawchenko & Gordon 2022).

4.4 Participatory modelling process

The framework embeds participatory processes throughout model development and application, operationalising the social dialogue pillar. Stakeholder engagement occurs in four phases: (1) scoping workshops to define model objectives and boundaries, (2) co-design sessions to develop model structure and validate assumptions, (3) scenario workshops to explore alternative futures and evaluate trade-offs, and (4) implementation planning to translate simulation insights into policy actions. This participatory approach builds trust, integrates local knowledge, and ensures that simulations serve community needs (Harrahill & Douglas 2019; Nicola & Schmitz 2022).

4.5 Data requirements and implementation

The framework requires three data categories: (1) workforce data (demographics, skills, employment history, household composition), (2) community data (population, services, infrastructure, economic structure), and (3) operational data which is linked to macroeconomic trends creating cost and price volatility and therefore viability of the operation and unplanned closures (mine production costs, employment shifts, closure timeline, financial resources). Data sources include mine employment records, census data, local government administrative data, and community surveys. Implementation involves iterative model calibration using historical data, sensitivity analysis to assess parameter uncertainty, and validation against comparable closure cases (García-García et al. 2024; Valinejad et al. 2022).

4.6 Decent Work integration

The framework systematically integrates all the Decent Work pillars. Employment creation is addressed through the workforce transition module, which models alternative employment pathways, retraining effectiveness, and entrepreneurship support. Rights at work are reflected in employment quality metrics, wage dynamics, and labour standards across alternative sectors. Social protection is operationalised through the community resilience module, which models income support, healthcare access, housing stability, and service provision. Social dialogue is embedded in participatory modelling processes that engage workers, communities, and stakeholders throughout the framework's development and application (ILO 2022).

4.7 Evaluation metrics

The framework employs comprehensive evaluation metrics aligned with Decent Work principles: (1) employment rate and quality (wages, benefits, job security), (2) income security and poverty rates, (3) service access (healthcare, education, utilities), (4) population stability and migration patterns, (5) social cohesion indicators (community participation, trust, identity), and (6) stakeholder satisfaction with transition processes. These metrics enable a holistic assessment of closure outcomes beyond narrow economic indicators (Harrahill & Douglas 2019; Blackwell & Dollery 2017).

Table 2 Framework components

Framework component	Simulation capability	Decent Work pillar (intended, untested)	Data requirements	Precedent source(s)
Workforce transition (ABM)	Heterogeneous worker/household decisions: job search, retraining, retirement, migration	Could address employment creation, rights at work	Worker demographics, skills, and employment history	Valinejad et al.(2022)
Community resilience (ABM)	Population change, service provision, and infrastructure transition	Could address social protection	Census data, service provision, infrastructure	Valinejad et al. (2022, behavioural network precedents)
Operational timeline integration (social digital twin component)	Integrates corporate closure horizons and milestone data to supply real-time lead time to community agents; conceptual integration mechanism	Enabling input across pillars	Operational data, financial resources	Lehmann et al.(2023); Cranford (2023)
Policy/scenario analysis	Compare interventions: social protection, retraining, investment, timing	Could address all pillars	Policy parameters, budget constraints	García-García et al.(2024, system dynamics); Krawchenko & Gordon (2022)
Participatory role-playing process	Stakeholder co-design and negotiation coupled to the ABM	Could address social dialogue	Stakeholder input, local knowledge	Étienne (2013); Barreteau et al. (2003) (for computational companion modelling); Nicola & Schmitz (2022) (for empirical justification of discordant stakeholder agendas)

This integrated framework adapts proven methodologies from energy and manufacturing transitions to the context of mine closure, providing a comprehensive tool for operationalising just transition principles and Decent Work in extractive industries.

5 Conclusion

This paper has proposed conceptually that the socio-economic dimensions of mine closure, long constrained by static, qualitative assessment methods, warrant simulation architectures currently being applied in other industrial transitions. While limited research has examined where these tools have not yet been explicitly deployed to address the human complexities of post-mine land use analysis, the literature offers proposed methodologies. Specifically, system dynamics captures aggregate macro-trajectories, (ABM) manages distributed, heterogeneous local behaviours, and SDTs virtualise complex human-centric spatial choices.

While this conceptual synthesis establishes a theoretical blueprint for adapting advanced digital simulations to the extractive sector, it opens several critical pathways for future empirical research. First, the immediate priority must be to move the integrated framework from a conceptual research design to localised, real-world pilot applications within specialised resource hubs. Future studies should focus on assembling high-fidelity datasets – integrating corporate workforce records, local government infrastructure capacities, and regional economic indicators – to calibrate the agent-based modules and stress-test the simulation engine against historical closure events.

Second, targeted research is required to mathematically formalise the behavioural rules governing split workforces. Future modelling efforts must refine how transient FIFO agents and localised residential agents dynamically respond to risk thresholds and changing employment horizons during an anticipatory decline phase. This includes capturing how information or economic anxiety diffuses through local social networks, triggering premature community exodus or labour bottlenecks.

Finally, the transition from a rigid corporate digital twin to an interactive 'social digital twin' requires institutional research into data governance frameworks. Future scholarship must explore mechanisms to resolve the tension between corporate data proprietary walls and the public transparency required for authentic co-design. Establishing standardised protocols for secure, bidirectional data sharing will be essential for validating these models across cases, ensuring that simulation architectures can be leveraged by regulators and operators alike to secure long-term regional economic resilience and uphold Decent Work standards.

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Use of artificial intelligence disclosure statement

In the preparation of this work, the author used Google Gemini 3 (2026) to produce images, SciSpace Enterprise edition 2026 to support citations and academic literature, and Grammarly Pro 2026 to improve writing and check use of citations in text. The authors have reviewed the content and edited it where required and take full responsibility for said content.

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