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A GENAI-ENHANCED FRAMEWORK FOR AGENT-BASED SUPPLY CHAIN SIMULATION: INTEGRATING UNSTRUCTURED DATA WITH STRATEGIC DECISION MODELLING

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ABSTRACT

This paper introduces a methodological framework integrating Generative Artificial Intelligence (GenAI) with agent-based simulation modelling for managing supply chain (SC) resilience. Traditional simulation approaches rely on structured datasets and verbal descriptions, limiting their ability to capture real-world SC dynamics driven by unstructured information streams. Our proposed framework addresses this limitation by developing a Retrieval-Augmented Generation (RAG) pipeline powered by Large Language Models (LLMs) that systematically extracts structured insights from unstructured sources, including policy documents, news archives, and market reports. The GenAI-enhanced framework improves simulation realism and reveals context-dependent strategic reserve effectiveness. We demonstrate the framework's effectiveness through India's lithium carbonate strategic reserve planning, modelling a multi-echelon SC spanning mining, processing, trading, port, manufacturing, and reserve management operations.

1 INTRODUCTION

Supply chain (SC) simulation faces a fundamental challenge: the increasing importance of unstructured information streams that traditional modelling approaches cannot effectively process. Whilst agent-based simulation has proven valuable for analysing complex SCs, conventional methods encounter significant challenges in obtaining reliable and up-to-date data for system agents. Such resource-intensive efforts typically depend on verbal descriptions and structured datasets within specific data silos, frequently failing to capture real-world SC operations and stakeholder behaviours shaped by rapidly evolving information landscapes. This challenge is particularly evident in critical mineral SCs, where swiftly changing geopolitical developments and market dynamics generate vast amounts of scattered insights across unstructured data streams. News articles, policy documents, and market reports contain hidden patterns revealing SC vulnerabilities and opportunities that traditional data collection methods struggle to identify and synthesise systematically. Whilst GenAI presents significant potential to address these methodological limitations, current applications focus primarily on algorithmic optimisation rather than enhancing input modelling capabilities. This research introduces a methodological framework leveraging GenAI to systematically process unstructured textual data for informing simulation model logic and parameters, thereby bridging the gap between information-rich but unstructured real-world contexts and structured simulation requirements.

2 INTEGRATED GENAI AND SIMULATION FRAMEWORK

We proposed a framework that integrates a GenAI-enhanced data extraction pipeline and simulation modelling for SC decision-making (Figure 1). The methodological innovation centres on systematically processing unstructured documents related to SC dynamics and transforming scattered insights into structured simulation inputs through automated extraction pipelines. Specifically, the proposed pipeline employs a RAG architecture to process unstructured documents such as news articles and policy documents related to critical minerals.

To validate the methodological framework, we developed a country-level multi-echelon agent-based model simulating India's lithium carbonate SC and strategic stockpiling policies. The model, implemented in Mesa, comprises six agents (mining, processing, trading, port, manufacturing, and reserve agents) addressing five critical stockpiling decisions: acquisition timing, sourcing strategy, inventory management, release triggers, and release quantities across different market scenarios (oversupply, balanced, deficit). In this case, we extracted insights that included identifying 224 distinct policy-driven market events (e.g., export restrictions), details on 89 strategic reserve initiatives across countries, and 68 specific stockpile creation or expansion activities. To ensure the reliability of our data, we implement an automated rule-based validation check system that rejects non-compliant JSON data (e.g., entries with missing or empty required fields such as 'relevant minerals'). The output also includes a direct quote from the original source for human verification before the information is accepted and further processed. Model parameters were calibrated by combining baseline data from public sources with contextual insights extracted from the GenAI pipeline. Through validation of the simulation model with historical data, we confirmed that the model replicates real-world scenarios and demonstrated the effectiveness of the framework.

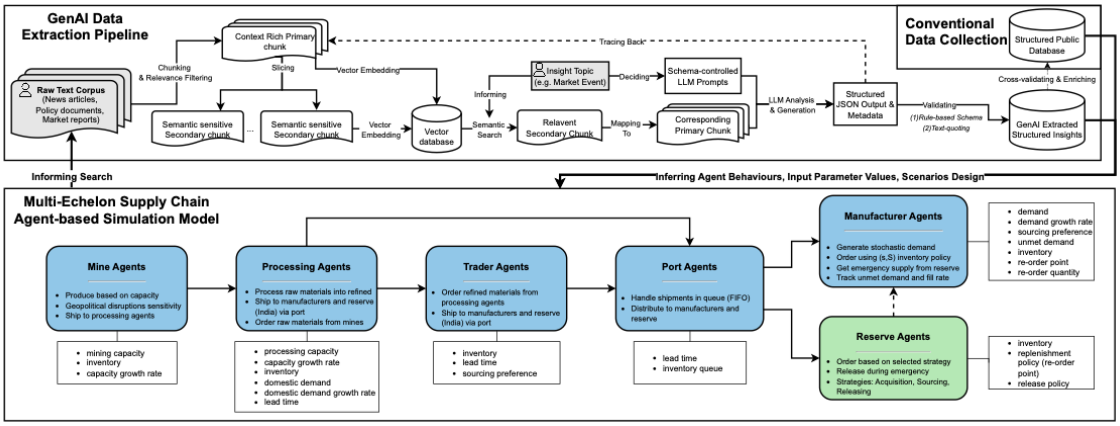

Figure 1: GenAI-enhanced simulation framework: data pipeline integrated with critical mineral SCs.

3 RESULTS AND CONCLUSION

The simulation results demonstrate that the effectiveness of strategic reserve policies is context-dependent and provide strategies in certain scenarios. The results also reveal a key trade-off associated with stockpiling. While reserves function as effective "shock absorbers" by improving service levels from 64.61% to 74.91% during a simulated geopolitical disruption, they achieve this by delaying stock depletion, which may result in increased long-term supply variability once the buffer is exhausted in resource-constrained environments (Figure 2). Our methodological contribution is developing a GenAI-enhanced framework that enhances simulation data credibility and improves strategic decision-making interpretability. Future work will assess reliability through expert-reviewed benchmarking against human raters and evaluate GenAI's contribution via controlled experiments of manual vs. GenAI inputs.

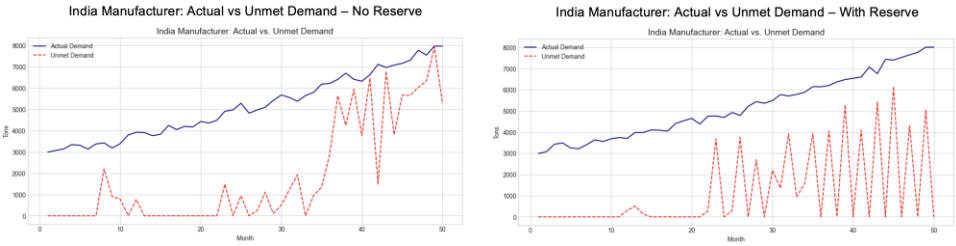

Figure 2: Simulation results -oversupply scenario with rapid depletion and export ban starting in month 5.