Sustainable Management of Rare Earth Elements for Clean Energy Using Prescriptive Digital Twins

Promoting Eco-Friendly Practices and Efficient Resource Management

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Introduction

Global demand for **clean energy technologies** like **electric vehicles (EVs)** and **wind turbines (WTs)** is increasing rapidly. By 2030, **EV adoption** is projected to reach **30%** of global car sales, and wind energy capacity is expected to grow by **9% annually** [1]. As the world transitions towards a greener future, the need for **Rare Earth Elements (REEs)**, such as **Neodymium (Nd)** and **Dysprosium (Dy)**, which are critical for the production of **permanent magnets** used in these technologies, will surge.

Background and Problem Statement

As global demand for clean energy continues to surge, driven by technologies such as electric vehicles (EVs), battery storage, wind power, and hydrogen, the reliance on Rare Earth Elements (REEs) grows significantly. Clean energy is projected to account for 90% of new global electricity capacity by 2027, with offshore wind turbines requiring large amounts of neodymium (Nd) and dysprosium (Dy). EV sales in Europe alone increased by 25% in early 2023, and the use of neodymium in EV batteries is expected to rise elevenfold by 2032[2].

However, this growing dependence on REEs poses significant challenges. With 90% of the global REE supply controlled by China, supply chain vulnerabilities create serious risks related to availability, cost, and geopolitical tensions. Furthermore, the extraction of REEs results in severe environmental degradation, including soil erosion, deforestation, and the generation of toxic waste, especially in mining-intensive regions.

Proposed Solution

To address the challenges of **Rare Earth Element (REE) extraction** and support **sustainable clean energy technologies**, we developed a **Prescriptive Digital Twin [4]** to optimize the entire REE supply chain. This system integrates real-time data collection from IoT sensors and advanced analytics to provide prescriptive recommendations for energy efficiency, waste reduction, and operational optimization at each stage of the extraction process.

Our proposed **Prescriptive Twin** will:

- ✓ **Optimize production** for efficient and sustainable resource extraction.
- ✓ **Minimize environmental impact** by reducing waste and emissions.
- ✓ **Reduce supply chain risks** through global operation optimization and resource management.

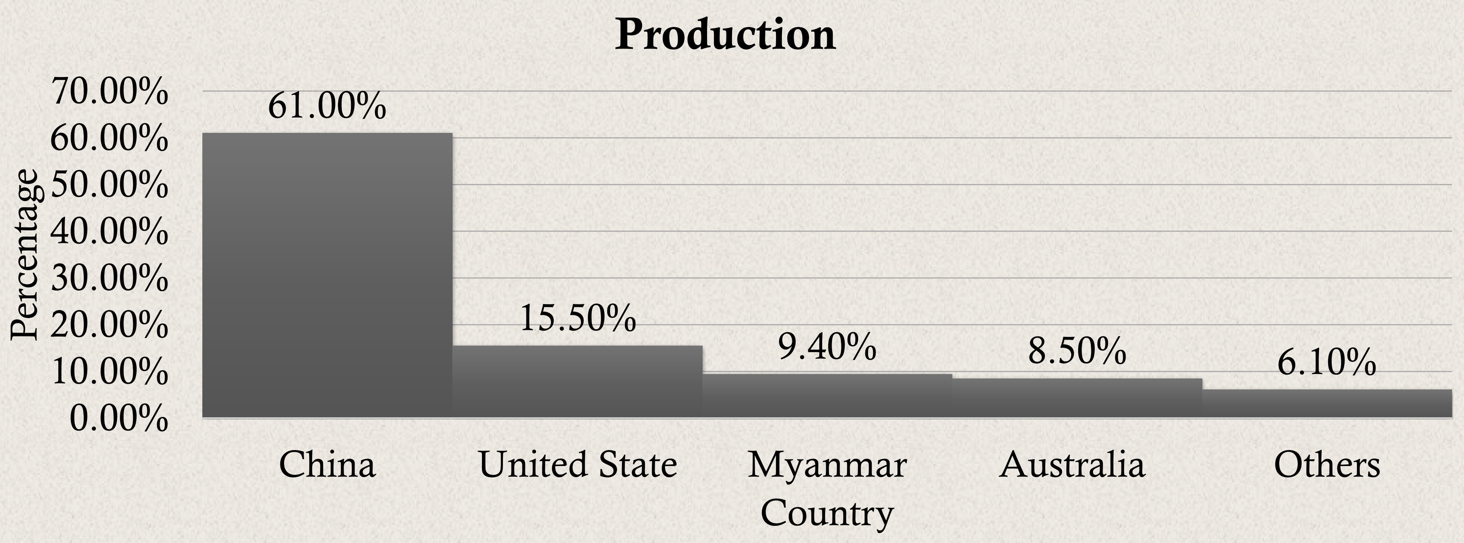

Figure 2: Leading countries share of global mine production in 2021[3]

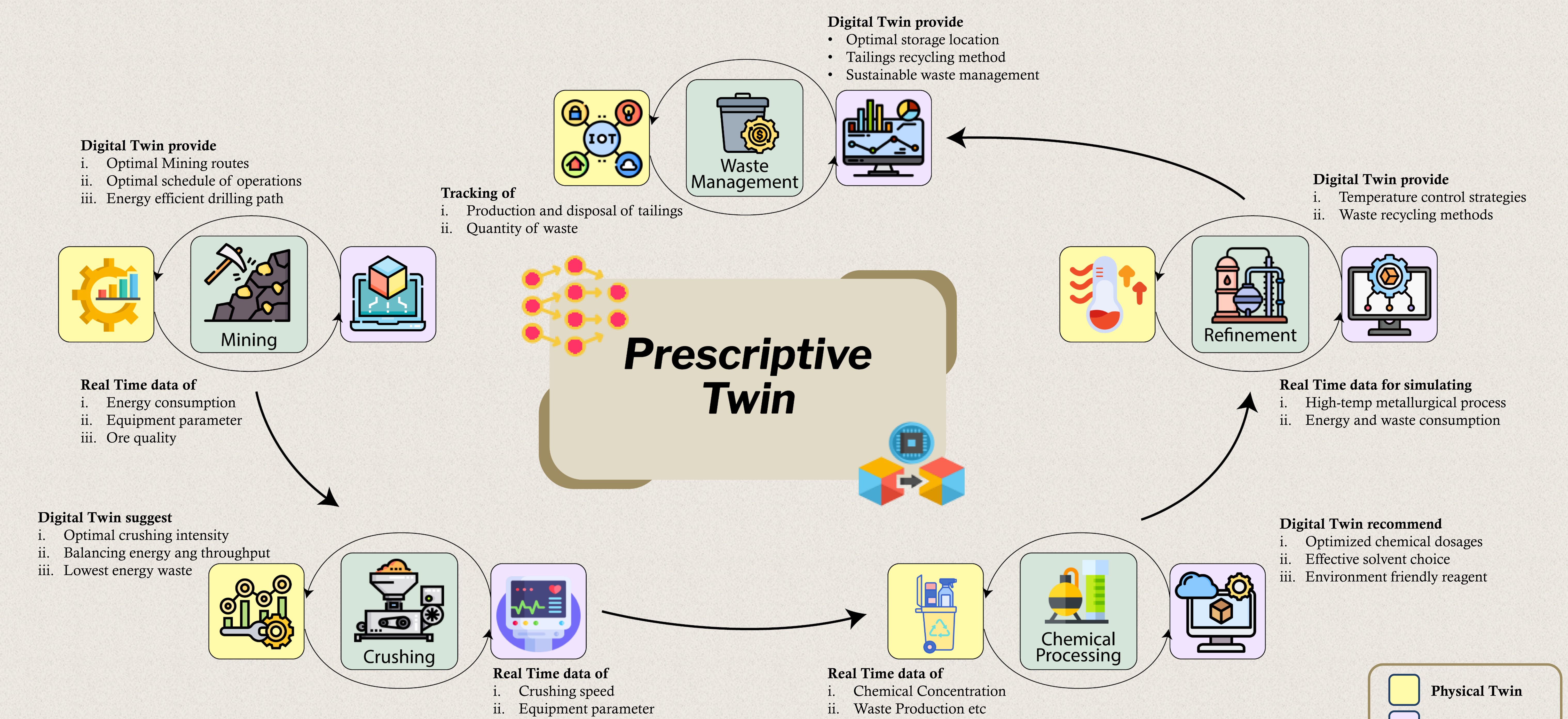

Figure 1: Prescriptive Twin

Prescriptive Twin Methodology and Components

Components or our proposed Digital Twin:

1. **Mining**: The digital twin provides real-time monitoring of **energy consumption** and the **efficiency of drilling operations**. By analyzing resource distribution, it can prescribe **optimal drilling paths** to minimize environmental degradation, reduce energy use, and limit unnecessary excavation.
2. **Crushing**: In the crushing phase, the digital twin tracks the performance of crushing equipment and energy consumption. It prescribes **adjustments to crushing intensity** and operational parameters to maximize efficiency while minimizing energy waste.
3. **Chemical Processing**: The prescriptive twin optimizes **chemical dosages** used during separation and extraction of REEs. By monitoring chemical concentration levels in real-time, it prescribes the **ideal number of solvents** and **processing times** to minimize toxic byproducts. This leads to a reduction in harmful waste, ensuring that the environmental impact is kept to a minimum.
4. **Refinement**: During refinement, the digital twin manages **high-temperature processes** and ensures **energy efficiency** by prescribing **optimal energy usage levels** and **emission controls**. This not only reduces **CO2 emissions** but also lowers costs by ensuring energy is only used when necessary.
5. **Waste Management**: Finally, the digital twin plays a critical role in **tailings management**, ensuring efficient **recycling** of waste materials. It tracks **waste production** in real time and prescribes the **optimal methods** for storing or reusing tailings, reducing environmental contamination risks and contributing to a more **circular economy** in REE extraction.

This 5-step approach ensures that the entire REE extraction process is **resource-efficient**, **environmentally friendly**, and **resilient** to global supply chain disruptions., enabling us to achieve sustainable outcomes at every stage of the process.

Discussion

Our **Prescriptive Digital Twin** significantly contributes to improving the sustainability of REE extraction processes by continuously adjusting operations based on real-time data. This dynamic optimization leads to **notable reductions in energy consumption and chemical waste**, allowing for more environmentally friendly production methods. By simulating demand fluctuations and production risks, the digital twin also helps alleviate **supply chain challenges**, ensuring better **material availability** and smoother operations. Furthermore, the integration of **recycling and reuse** techniques promotes substantial waste reduction, moving the industry closer to adopting a **circular economy**. In terms of environmental impact, optimizing energy-intensive steps such as **crushing,** and **refinement** is expected to reduce **CO2 emissions** and the overall **carbon footprint** of REE extraction. Finally, the twin ensures safer waste disposal practices by improving **waste management**, which reduces the risk of **soil erosion** and **water contamination**, further supporting the shift towards **sustainable and eco-friendly extraction** practices.

Conclusion and Future Directions

Prescriptive Digital Twins enable data-driven, eco-friendly REE extraction while mitigating environmental damage. The twin ensures resource efficiency and supply chain resilience, contributing to the sustainable growth of the clean energy sector.

Future implementations will integrate Reinforcement Learning (RL) to further optimize real-time decisions under changing conditions. Physics-Informed Neural Networks (PINNs) can be incorporated to simulate more complex physical processes in REE extraction, leading to adaptive solutions under variable environmental and economic conditions.

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