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I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

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Abstract

The present thesis assesses the export logistics system supplying Erdenet Mining Corporation (EMC), Mongolia's premier copper concentrate exporter and state-owned mineral enterprise representing 13.5 percent of Mongolia's GDP. Scope included material flow from the Erdenetiin-Ovoo mine and the 164 km long Erdenet rail spur as well as the Trans-Mongolian Railway mainline and border crossing at Zamyn-Uud/Erenhot to the Inner Mongolia Autonomous Region of China.

The 2022-2025 audited financial statements show operating cost-per-tonne rising 57.8 percent over the four years whilst profit-per-tonne saw little change, hitting a low of MNT 1.315 million in 2025 from MNT 1.328 million in 2022.

Revenue per tonne grew 42.1 percent-substantially slower than cost growth, indicating structural erosion of operational efficiency that favorable copper prices have partially masked.

The Theory of Constraints based bottleneck analysis determines the border crossing between Zamyn-Uud and Erenhot to be the system bottleneck. Actual observed border crossing times average from 27 to 37 hours per train, resulting in a Process Cycle Efficiency of less than 10%. Secondary constraints include uncoordinated scheduling on the Erdenet-Darkhan spur and the routing of all through-freight via the congested Ulaanbaatar urban corridor.

Three optimization phases are proposed. Phase 1 implements Electronic Data Interchange pre-clearance protocols, Authorized Economic Operator classification, and dedicated unit train scheduling. Phase 2 leverages the Bogdkhan Railway Bypass, currently under construction and expected to open in November 2026, to eliminate the Ulaanbaatar bottleneck and enable a 13 percent volume increase. Phase 3 evaluates construction of a greenfield copper smelter to increase product value density by a factor of 4.6 and permanently eliminate Treatment and Refining Charge exposure.

Financial modeling under base, case assumptions demonstrates that full system optimization yields an EBITDA uplift of USD 284 million per year, expanding the EBITDA margin from 28.8 percent to 40.2 percent. The Mongolian state budget contribution increases from USD 632 million to USD 952 million annually - a USD 320 million increment. The smelter project generates a positive Net Present Value of USD 850 million at an 8

percent real discount rate, with a break-even copper price of USD 9,500 per tonne - well below current market levels.

Keywords: *Mining Logistics, Industrial Engineering, Bottleneck Analysis, Theory of Constraints, Copper Smelting, Financial Impact Assessment, Mongolia, Erdenet Mining Corporation*

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List of Abbreviations

AEO	Authorized Economic Operator
CAPEX	Capital Expenditure
CAREC	Central Asia Regional Economic Cooperation
CIT	Corporate Income Tax
DCF	Discounted Cash Flow
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization
EDI	Electronic Data Interchange
EMC	Erdenet Mining Corporation
FEED	Front-End Engineering Design
GDP	Gross Domestic Product
JCC	Joint Customs Control
LME	London Metal Exchange
MNT	Mongolian Tögrög
NPV	Net Present Value
NVAT	Non-Value-Added Time
OPEX	Operating Expenditure
PCE	Process Cycle Efficiency
SOE	State-Owned Enterprise
SX/EW	Solvent Extraction and Electrowinning
TC/RC	Treatment Charge and Refining Charge
TOC	Theory of Constraints
UBTZ	Ulaanbaatar Railway (Mongolian-Russian Joint Venture)
USD	United States Dollar
VAT	Value-Added Time
RQ	Research Question

Chapter 1: Introduction

1.1 Industrial Context and System Definition

As a landlocked nation, Mongolia's economy is built around a mineral resource sector that is narrow but highly productive. Mining makes up around 24 percent of GDP, more than 90 percent of exports [1], and provides the financial backbone of Mongolia as a state. Within Mongolia's mining sector, Erdenet Mining Corporation (EMC) is unique: one company responsible for roughly 13.5 percent of Mongolia's total GDP [2] and almost 10 percent of all state and local government revenue.

Situated in Orkhon Province in north-central Mongolia, EMC operates the Erdenetiin-Ovoo copper, molybdenum porphyry deposit, which produces one of the top four highest volumes of copper per year globally. EMC set production records in 2025 by mining 47.1 million tonnes of ore [2], processing 39.9 million tonnes of that ore, and exporting 574,987 tonnes of copper concentrate. Total sales revenues equated to MNT 4.89 trillion (~USD 1.38 billion), of which taxes, royalties, and dividends totaled MNT 2.31 trillion, EMC's largest contribution to Mongolia's state budget in its 47-year history. EMC was established in 1978 as a joint venture between Mongolia's Mongolian People's Republic and its Soviet neighbor; when the Soviet Union collapsed, the mine was reconstituted as a Mongolian state-owned enterprise. The Mongolian state owns a majority stake of 51 percent with its Russian neighbor possessing the remaining 49 percent, which it divested in 2016 to transfer full ownership of EMC to Mongolia. The company currently employs over 8700 workers, one of Mongolia's largest single employers – and its namesake city, Erdenet, which depends on the mine and has a population of around 100,000 residents. Given this context, it is clear that decisions regarding EMC's logistics system impact more than just the efficiency of material movement: they affect jobs, infrastructure, regional economic development, and Mongolia's ability to provide public services through taxation. Mongolia's reliance on mineral exports only amplifies this importance. The country contains estimated proven and probable reserves of copper, coal, gold, fluorspar, and rare earth minerals that stand among the largest in the world on a per capita basis (Nation's population: 3.4 million). Mongolia is landlocked by Russia to its north and China to its south, and therefore, almost all mineral exports must travel through one of these countries to reach international markets. Over 90 percent of mineral exports, and therefore revenues, flow south through China. Mongolia earned 90.3 percent of its total revenue from exports from China in 2024 [3]. For commercial and geopolitical reasons, it is therefore critical that every stage of the supply chain operate as

efficiently as possible. Despite these headline results, a detailed examination of financial data from 2022 through 2025 reveals a structural deterioration in operational efficiency that favorable copper prices have partially masked. Per-tonne operating costs increased 57.8 percent over this period while profit per tonne fell by 1.0 percent, ending 2025 only marginally above 2022 levels. The system that moves concentrate from the mine to Chinese smelters, a 1,400-kilometer chain of rail, border processing, and customs clearance - has become a source of compounding inefficiency rather than competitive advantage. Despite the importance of this logistics system, existing studies have not provided an integrated engineering and financial analysis at the firm level that links operational bottlenecks to measurable economic outcomes, in the Mongolian context.

The export logistics system comprises three subsystems. The first is a 164-kilometer dedicated rail spur connecting the Erdenet mine to the Trans-Mongolian Railway mainline at Darkhan. This single-track, non-electrified branch line carries all outbound concentrate and inbound supplies. The spur was constructed between 1975 and 1978 to engineering standards appropriate for the traffic volumes of that era; maximum permitted axle loads of 23.5 tonnes constrain train payload per wagon, and the absence of electrification means all motive power is provided by diesel-electric locomotives operated by EMC's internal fleet. The single-track configuration with limited passing loop capacity means that loaded southbound and empty northbound train movements must be carefully scheduled to avoid conflicts, and that any unplanned delay to one movement cascades into delays for subsequent trains in both directions. The second is the Trans-Mongolian Railway mainline extending 1,110 kilometers from Darkhan through Ulaanbaatar to the border station of Zamyn-Uud, operated by UBTZ, the 50/50 Mongolian-Russian joint venture [4]. UBTZ operates this line under a concession from the Mongolian government but functions as a de facto monopoly on north-south rail freight. Its pricing structure for freight haulage is negotiated bilaterally with major customers including EMC, but tariff increases in recent years have contributed to EMC's rising per-tonne logistics cost burden. The mainline passes through Ulaanbaatar, Mongolia's capital and home to nearly half the national population, where the railway alignment runs through the urban fabric of the city across 32 at-grade level crossings [5]. The third is the Zamyn-Uud/Erenhot border interchange node, where Mongolian broad-gauge wagons interface with China's standard-gauge network, and where customs, inspection, and gauge-change operations are carried out. This physical system has remained essentially unchanged since 1978, despite the extraordinary growth in trade volumes and the availability of modern logistics technologies that have transformed

comparable corridors elsewhere in the world. The absence of systemic modernization is a recurring theme in the baseline analysis that follows.

1.2 Problem Statement and Research Motivation

The principal problem confronting EMC's export logistics system is the progressive erosion of process efficiency across all three subsystems, combined with a product configuration that leaves significant value on the table at every stage.

Mongolia's reliance on mineral exports and landlocked position underscore the importance of supply chain efficiency: over 90 percent of mineral exports flow through China, making logistics optimization fiscally critical to sustaining Mongolia's national budget.

The Ulaanbaatar urban corridor introduces scheduling conflicts and velocity reductions that restrict corridor capacity. All through-freight must compete with passenger services, commuter trains, and local shunting operations across 32 at-grade road crossings that impose an average of 230 minutes of daily road closure within the capital. The Bogdkhan Railway Bypass, currently under construction, will resolve this constraint - but its commissioning in November 2026 means the bottleneck persists for the near term.

EMC's product - copper concentrate grading 22.5 percent copper - means that for every tonne of payable copper shipped, approximately 3.4 tonnes of gangue, moisture, and inert material travel the full 1,400 kilometers. This low value density amplifies the financial cost of every logistics inefficiency. Treatment and Refining Charges further reduce EMC's realized copper price relative to the London Metal Exchange benchmark, although the current near-zero TC/RC environment temporarily masks this structural disadvantage [6]. This motivates the need for a structured, system-level analysis that combines bottleneck identification, process optimization, and financial evaluation to support evidence-based decision-making.

1.2a Research Aim

The aim of this study is to analyze and optimize the export logistics system of Erdenet Mining Corporation by identifying system bottlenecks and evaluating engineering and infrastructure interventions that improve throughput, reduce cycle time, and enhance economic performance.

1.3 Engineering Objectives

The primary objective of this thesis is to analyze and evaluate process and infrastructure modifications that maximize system throughput, minimize cycle time, and improve product value density for EMC's export logistics chain. The specific technical objectives are:

- Characterize baseline system performance using audited operational and financial data from 2022 through 2025, establishing per-tonne cost, revenue, and efficiency metrics.
- Identify the primary bottleneck limiting total system throughput using the Theory of Constraints analytical framework.
- Model the impact of Electronic Data Interchange pre-clearance protocols and Authorized Economic Operator certification on border dwell time.
- Calculate the incremental throughput capacity enabled by the Bogdkhan Railway Bypass and quantify its financial impact on EMC's volume and EBITDA.
- Perform a techno-economic feasibility assessment for an on-site copper smelter, including mass balance, capital expenditure estimation, and discounted cash flow analysis.
- Integrate per-optimization financial impacts into a consolidated model of EMC's projected income statement under full system optimization.

These objectives are structured to address the research problem through sequential analysis of system performance, bottleneck identification, optimization modelling, and financial evaluation.

This study addresses the following research questions:

- RQ1: What are the primary bottlenecks limiting throughput in EMC's export logistics system?
- RQ2: How can process and infrastructure interventions reduce cycle time and improve system efficiency?
- RQ3: What is the economic impact of the proposed optimization measures?
- RQ4: Which combination of optimization measures provides the greatest overall system and financial benefit?

1.4 Scope and System Boundaries

The modeled system boundary includes the conveyor belt from copper concentrate stockpile at Erdenet mine complex to Chinese smelter gate. Mining, Comminution and flotation upstream from the copper stockpile are fixed at 2025 baseline production for Phase 1 and 2 scenarios. Phase 3 includes shift in output specification from concentrate to copper cathode, which has fundamental impact on both transport volume and product price.

MNT/USD exchange rate used for all financial considerations in historical comparisons is 3,481 Mongolian Tugrik (MNT) to USD, which is the annual average reported by Bank of Mongolia for 2025. This same rate is applied to forward financial estimates unless otherwise specified. Market price is based on quoted LME copper price. Base-case assumption going forward is USD 12,000 per tonne, which is average analyst prediction for 2026–2027.

Chapter 2: Technical Background and Literature Review

2.1 Heavy-Haul Rail and Bulk Material Logistics

Heavy-haul rail systems are designed to transport large volumes of bulk commodities with high axle loads of 25 to 40 tonnes and long train consists exceeding 100 wagons per movement [27]. Economic viability depends on sustained high asset utilization and maximized net tonne-kilometers per locomotive-hour. The preferred operating model for high-volume bulk commodities is unit train operation, in which a complete consist moves as a block from origin to destination without intermediate switching or remarshalling. Unit trains eliminate classification yard delays and improve wagon cycle time predictability. The literature on heavy-haul rail efficiency is extensive, with foundational contributions from Van Der Meulen and Möller [7], who demonstrated that fixed-interval scheduling in dedicated bulk corridors reduces average wagon cycle time by 18 to 24 percent compared to demand-driven departure scheduling. Krueger [27] established the canonical framework for capacity analysis on single-track railways, showing that line capacity is a function of train meet and pass constraints at sidings, and that heterogeneous traffic mixes - combining high-priority passenger services with lower-priority freight - disproportionately reduce effective freight capacity relative to homogeneous operations. These findings are directly applicable to the Trans-Mongolian Railway, where EMC's concentrate trains share the mainline with passenger services and general freight under scheduling arrangements that do not systematically prioritize high-value bulk movements. Supply chain theory can be considered here as well, specifically supply chain integration as described by Christopher [26]. Supply chain integration theory states that the cost of a given supply chain is lowest when decisions are made across the entire chain, rather than optimizing each node independently. Translated into the Erdenet problem, improving conditions at the border node should be designed jointly with any scheduling changes on the spur and mainline, and modeling should account for interactions between nodes rather than optimizing each bottleneck separately. The absence of this integrated perspective in prior Mongolia logistics studies represents one of the central gaps this thesis addresses.

Key performance metrics in bulk rail logistics include gross tonne-kilometers, net tonne-kilometers, wagon cycle time from loading to return to loading, and locomotive utilization measured as operating hours per day. Unit train operation is utilized in Erdenet however the system does not follow a fixed interval schedule that would optimize these values. Train departure times are negotiated on a case-by-case basis with UBTZ instead of referring to a

set timetable. This creates variability that is amplified throughout the downstream process. Two similar mineral export corridors have been used as benchmark for comparison. Transnet Freight Rail's iron ore corridor between Sishen and Saldanha, South Africa maintains a wagon cycle time of about 5.8 days [7] for an 861 kilometer, single-commodity rail line by strictly adhering to a set schedule and having infrastructure dedicated to that corridor. Western Australia's Pilbara heavy haul network operates at asset utilization rates of over 92 percent [4] by utilizing automated train control and centralized traffic scheduling. While these systems operate at throughput volumes an order of magnitude larger than Erdenet's and benefit from purpose-built infrastructure, the scheduling and information management practices they employ are transferable principles applicable regardless of scale. The fundamental lesson from these benchmarks is that the largest efficiency gains in bulk rail logistics come not from capital expenditure on new infrastructure but from operational and informational reforms that extract more capacity from existing assets - precisely the logic underpinning Phase 1 of this thesis's optimization framework.

2.2 Theory of Constraints and Value Stream Analysis

The Theory of Constraints (TOC) is used to identify the single constraint limiting system throughput [8]. Applied to Erdenet, TOC analysis identifies the Zamyn-Uud/Erenhot border interchange as the primary constraint. Value Stream Mapping [9] complements TOC by distinguishing value-added from non-value-added time, with the Process Cycle Efficiency metric directly indicating improvement potential.

Applied to the Erdenet export logistics system, TOC analysis identifies the Zamyn-Uud/Erenhot border interchange node as the primary constraint. The node's processing capacity - measured by throughput trains per day - is lower than the upstream spur and mainline capacity. Dwell time variability at the node creates queue formation that forces EMC to maintain higher than necessary inventory buffers at both the mine and the border.

Value Stream Mapping complements the TOC framework by distinguishing value-added time (VAT) from non-value-added time (NVAT). In the context of the Erdenet export system, value-added time is defined as the period during which the concentrate physically moves toward its destination. All stationary periods - waiting, inspection, documentation, and queue time - constitute non-value-added time. The ratio of VAT to total lead time is the Process Cycle Efficiency, a metric that directly indicates the scope for improvement. While TOC has been widely applied in manufacturing systems, its application to national-scale logistics

systems - particularly in mining export corridors - remains relatively limited, highlighting a gap addressed by this study.

2.3 Border Interchange Node Operations

Border crossing of railways of different track gauge widths is one of the fundamental technical challenges in international rail freight corridors [27]. At Zamyn-Uud/Erenhot, Russian-gauge wagons (1,520 mm) from Mongolia must transfer cargo to Chinese standard-gauge wagons (1,435 mm) per International Union of Railways standards [27]. Usually, bogie exchange is practiced. The wagon chassis is unloaded and reloaded with the help of special hydraulic bogie lifting jacks. This operation requires a stock of compatible bogies on both sides of the border. The technical literature distinguishes three main approaches to gauge discontinuity: wagon transfer (transloading cargo between wagons of different gauges), bogie exchange (replacing the entire wheel assembly under each wagon), and variable-gauge axle systems (where axle width adjusts automatically on a gauge-changing installation) [27]. Bogie exchange, the method used at Zamyn-Uud/Erenhot, offers a reasonable balance between capital cost and throughput rate for medium-volume corridors, but is mechanically labor-intensive and creates a bottleneck when wagon supply is constrained on either side of the interface. The Brest-Terespol interchange between Poland and Belarus, operating at significantly higher volumes than Zamyn-Uud/Erenhot [4], demonstrated in a 2019 operational review that bogie exchange throughput is primarily limited by wagon availability rather than the exchange procedure itself - a finding directly corroborated by the empirical data at Zamyn-Uud/Erenhot, where wagon shortage waiting time accounts for 7.5 hours of the 32-hour average dwell time. The trade facilitation literature provides the policy framework for reducing administrative processing times at border crossings. The World Customs Organization's SAFE Framework of Standards, updated in 2021 [11], establishes the theoretical basis for pre-arrival processing, risk-based targeting, and Authorized Economic Operator programs as the global best practice architecture for secure, efficient cross-border trade. Wilson, Mann, and Otsuki [12] estimated that a one-day reduction in border processing time is equivalent in trade facilitation terms to a reduction of import tariffs by 1.1 percentage points - a finding that gives quantitative weight to the argument for border modernization at Zamyn-Uud/Erenhot. Portugal-Perez and Wilson [13] further showed that trade facilitation improvements have disproportionately large effects on developing country exporters of natural resources, because their export products are relatively undifferentiated and therefore highly sensitive to logistics costs. This finding is particularly pertinent to Mongolia, where copper concentrate is a commodity product for

which price differentiation from competitors is impossible and cost competitiveness is the only lever available to improve market position.

Customs and trade facilitation technologies have substantially reduced border processing times in comparable international settings. Electronic Data Interchange enables computer-to-computer transmission of standardized trade documents in advance of cargo arrival. Single Window systems aggregate all government agency interactions into a single submission point. Authorized Economic Operator certification, granted to businesses meeting supply chain security and compliance standards, confers automatic green-channel processing and reduced inspection frequency.

The China-Mongolia Joint Customs Control framework, operational since May 2014 and expanded to all five major bilateral border crossings, enables real-time sharing of weighbridge data and scanner imagery between customs authorities. When an electronic manifest is submitted 48 hours before train departure, both customs authorities can complete risk assessment before the train arrives at the crossing, enabling simultaneous rather than sequential processing.

A 24-hour border crossing pilot operated at Zamyn-Uud/Erenhot from April to September 2024 [14]. The pilot demonstrated reduced queuing and congestion, and Mongolia formally requested permanent 24-hour operation in October 2024. China Railway Hohhot Group, the operator of the Chinese side, confirmed in July 2025 [15] that border inspection time had been cut to under 30 minutes and that a full digital port system for paperless clearance was under development. However, existing studies primarily describe operational improvements without quantifying their system-wide economic impact, which limits their usefulness for decision-making.

2.4 Pyrometallurgical Processing of Copper Concentrates

Copper smelting converts sulfide concentrate to refined copper cathode through Flash Smelting technology (industry standard for large-scale production) [16]. The process produces copper matte (~65% copper) which is then refined through Peirce-Smith converters and electrorefining to LME Grade A cathode (99.99% copper). Technology achieves 96-98% copper recovery and generates sulfuric acid byproduct [16]. Mass reduction from concentrate to cathode is approximately 4.6 to 1.

Cathode is also a globally traded commodity sold directly at or near the LME spot price. Concentrate, by contrast, must be discounted for Treatment and Refining Charges that

represent the smelter's processing fee. Under normalized market conditions, these charges range from \$30 to \$80 per tonne of concentrate, equivalent to a discount of \$133 to \$356 per tonne of contained copper at 22.5 percent grade. Producing cathode onsite eliminates this discount entirely. The environmental profile of copper smelting requires explicit treatment because it directly affects project feasibility in Mongolia's regulatory environment. Flash Smelting generates sulfur dioxide gas as an unavoidable byproduct of sulfide oxidation. Modern smelters capture SO_2 as sulfuric acid using double-absorption acid plants, achieving SO_2 capture rates of 99.5 percent or higher. The resulting sulfuric acid is itself a valuable industrial commodity: global production of byproduct copper smelter acid amounts to approximately 16 million tonnes per year, and demand in Mongolia's domestic market - primarily agricultural fertilizer production and mining heap-leach operations - could absorb a portion of the proposed smelter's estimated 400,000-tonne annual acid output. The remainder would require export, most plausibly to Chinese industrial markets via the existing rail corridor, partially offsetting the logistics cost reduction achieved by switching from concentrate to cathode export. Water consumption is a second environmental constraint of significance in the Orkhon Valley context. Flash Smelting followed by electrorefining requires an estimated 5-8 m³ of water per tonne of cathode. At a production rate of 150,000 tpa of cathode, this equates to 750,000 - 1,200,000m³ water per year, representing significant new consumption from the Orkhon River basin which experiences dry seasons. This water balance issue should be explicitly considered in an EIA for the proposed project, and solutions such as dry-stack tailings facilities, water re-circulation loops, and process cooling optimization should be designed into the engineering scope to reduce overall water consumption. Finally, a greenfield pyrometallurgical smelter represents a capital intensive expenditure when compared to Phase 1 and Phase 2 upgrades. Consulting cost estimates for similar greenfield projects [16] - notably the Udokan copper mine in Russia, the Kamoa-Kakula copper smelter expansion in the DRC, and the Kansanshi Smelter in Zambia - suggest a CAPEX range of USD 9,000 to 12,000 per annual tonne of cathode capacity for new Flash Smelting plants built in remote locations. At 160,000 tonnes annual cathode capacity and applying a USD 10,900 per tonne mid-range benchmark, the implied CAPEX for EMC's proposed smelter is USD 1.74 billion - consistent with the USD 1.75 billion estimate used in Chapter 5.3. This estimate excludes owner's costs, financing costs during construction, and the cost of supporting infrastructure including power supply upgrades, water treatment facilities, and acid storage and loading systems, which collectively may add 15 to 20 percent to the total investment requirement.

2.5 Previous Studies on Mongolian Mineral Logistics

ADB Mongolia Transport Sector Assessment [4] reports that the Trans-Mongolian Railway Line forms the backbone of freight traffic nationally, with line capacity reached or exceeded during peak seasons. The ADB's Bogdkhan Railway Bypass Investment Program documentation [10] provides the engineering basis for the bypass project evaluated in Chapter 5 of this thesis.

The World Bank Mongolia Corridor Assessment Report [5] identified Bogdkhan Railway Bypass as a priority infrastructure project. The report projects that the bypass will shorten travel time by 4 to 6 hours for through-freight and increase annual freight capacity of the north-south corridor by 5 to 6 million tonnes [5]. The CAREC Rail Transport Analysis 2020 fact sheet provides empirical data on actual dwell times at the Zamyn-Uud/Erenhot border, documenting a total processing time of 27 to 37 hours per freight train [4]. This analysis also highlights wagon availability as a regularly constraining factor in determining how quickly trains can clear the Chinese side of the border, independent of infrastructure improvements [4].

No previous study provides a product-specific, integrated engineering and financial analysis of the Erdenet copper concentrate export system. Although these studies provide valuable macro-level insights, none offer a firm-level, integrated engineering and financial analysis of a specific export system. This thesis addresses this gap by linking operational performance metrics with financial outcomes in a single analytical framework. The following chapter presents the methodological approach used to operationalize this integrated analysis.

Chapter 3: Methodology

3.1 Research Design

Where exact operational data are unavailable in published form, industry benchmark estimates from comparable open-pit copper mining and bulk rail logistics operations are applied. All assumptions are explicitly documented and subjected to sensitivity analysis. The deterministic model is supplemented by scenario analysis covering conservative, base-case, and optimistic assumptions for key variables. This approach enables a structured evaluation of system performance and the quantification of optimization impacts under clearly defined assumptions.

3.2 Data Sources and Validation

Operational and production data are drawn from EMC Annual Production Reports for 2022 through 2025 [2], UBTZ aggregated freight statistics, and the CAREC Rail Transport Analysis. Audited financial figures on total revenue, total costs, net profit and contributions to the state budget in both MNT and USD are derived from EMC's publicly disclosed audited financial statements and Ministry of Finance releases, and have been cross-checked with a variety of independent sources such as MONTSAME national news agency reporting [18] and Mining Insight Mongolia interviews [19] with EMC's General Director. Commodity pricing data is derived from LME daily settled prices, Fast markets [6] and Benchmark Mineral Intelligence [20] TC/RC benchmark quotations, and copper cathode premiums published by CRU Group. Benchmark capital and operating costs are based on the CRU Copper Smelter Cost Database and feasibility study publications from comparable greenfield projects including Kamoakakula, Kansanshi, and Udokan. Exchange rates used to convert MNT to USD are taken from Bank of Mongolia annual average reported exchange rates: 3,141 MNT/USD in 2022; 3,466 in 2023; 3,390 in 2024; and 3,481 in 2025. 2025 exchange rate is applied to forward years.

3.3 Key Performance Indicators

The analysis tracks three categories of performance indicators. Throughput and capacity metrics include annual concentrate throughput in tonnes, contained copper throughput in tonnes, mainline capacity utilization as a percentage, and border node throughput trains per day. Time-based metrics include total border dwell time per train, disaggregated by process step, and Process Cycle Efficiency as the ratio of value-added to total time. Cost and financial metrics include unit logistics cost per tonne of concentrate, unit operating cost per

tonne, EBITDA margin, and state budget contribution as a percentage of revenue. These indicators provide a basis for comparing baseline and optimized system performance.

3.4 Financial Modeling Framework

The baseline income statement is constructed from confirmed EMC financial disclosures and calibrated to the General Director's public statement that in 2025, costs fell below the 75-tugrug-per-tugrug-of-revenue threshold. The 2025 USD exchange rate of 3,481 MNT/USD is applied throughout.

Phase 3 smelter evaluation uses Discounted Cash Flow methodology. Net Present Value is calculated at an 8 percent real discount rate over a 25-year project life. Sensitivity analysis evaluates NPV across LME copper prices from USD 7,500 to USD 15,000 per tonne and TC/RC regimes from USD 0 to USD 80 per dry metric tonne. The smelter CAPEX estimate of USD 1.75 billion is a Class 4 estimate per AACE classification [16], with an expected accuracy range of minus 15 percent to plus 30 percent. The deterministic nature of the model ensures transparency, though it does not fully capture stochastic variability in logistics operations.

3.5 Research Framework

The research framework integrates system inputs (material flow, infrastructure capacity, and operational constraints), analytical tools (Theory of Constraints, value stream analysis, and financial modelling), and optimization scenarios to generate outputs in terms of system efficiency, throughput, and financial performance. This structured approach ensures alignment between research objectives, methodology, and expected outcomes.

Chapter 4: Baseline System Characterization (2022–2025)

4.1 Production Volumes and Material Flow

The total amount of ore milled increased from 37.8 million tonnes (Mt) in 2022 to 39.9Mt in 2025, the highest annual volume ever recorded. Copper concentrate production decreased steadily from 626,055 tonnes (Tn) in 2022 to 568,240Tn in 2024 and recovered slightly to 574,987 Tn in 2025. This reduction in concentrate production is the result of a decreasing ore grade: average concentrate grade decreased from 23.1 percent Cu in 2022 to 22.5 percent Cu in 2025 [1,2]. Total contained copper produced in concentrates declined from about 144,600Tn to 129,400Tn over this period. The reduction in ore grade should be expected. Erdenet is an open pit mine that began operation almost fifty years ago. As mining continues deeper into and around the pit, new material is derived from more and more lateral parts of the orebody which have lower grades of copper mineralization than earlier mined deposits. Analysts estimate economically mineable reserves in the Erdenetiin-Ovoo deposit will last another 20-30 years at current production levels [17]. However, if this grade trend continues, it will require an ever increasing amount of ore to be mined and processed for each tonne of concentrate produced. This is the principal reason processing costs have increased on a per tonne basis, as described in Chapter 4.3. The material flow analysis for 2025 reveals that the logistics system moves substantially more material than the contained copper value would suggest. At 574,987 tonnes of concentrate containing 22.5 percent copper, the system transports approximately 129,400 tonnes of payable copper embedded within 445,600 tonnes of gangue material, moisture, and impurities. At an average train payload of 3,500 tonnes and 164 southbound train movements per year, the system operates at an average departure interval of 2.22 days. This interval, combined with the 32-hour average border dwell time and approximately 48-hour mainline transit time, means the total wagon cycle time from the mine to the border and return is approximately 11 to 13 days under baseline conditions. Reducing this cycle time through the Phase 1 interventions analyzed in Chapter 5 would allow a larger proportion of the wagon fleet to complete additional rotations within the same calendar year, enabling volume growth without proportional fleet expansion.

The annual material flow volume required to support the 2025 Mine Plan is 574,987 tonnes of concentrate. Using an average payload of 3,500 tonnes per train, this equates to just over 164 loaded train movements per year southbound towards Zamyn-Uud, or one train departure every 2.2 days. Total system freight on the Trans-Mongolian Railway mainline (all

commodities) is currently estimated at approximately 22 million tonnes per year and is running at or near practical capacity. While EMC concentrate would represent only about 2.6 percent of total system throughput by weight, it would represent a disproportionately large share of total value.

4.2 Audited Financial Performance (2022–2025)

The four-year financial record reveals a pattern of rising revenue alongside accelerating costs, resulting in a net profit squeeze that is structurally significant despite appearing modest in absolute terms. Table 4.1 presents the audited financial data in MNT.

Table 4.1: EMC Audited Financial Summary, 2022–2025 (MNT billion)

Financial Indicator	2022	2023	2024	2025
Total Revenue (R)	3,746.6	4,026.4	3,973.9	4,890.5
Total Costs (C)	2,572.3	2,917.3	3,149.4	3,724.9
Net Profit (P)	831.2	803.0	578.5	756.7
Budget Contribution (B)	1,782.2	2,021.9	1,549.0	2,309.4
Copper Concentrate (tonnes)	626,055	603,487	568,240	574,987

Total revenues grew from MNT 3,746.6 billion in 2022 to MNT 4,890.5 billion in 2025 (EMC [2]), an overall increase of 30.5 percent. While this uptick was mostly attributable to higher copper prices, total operating costs surged from MNT 2,572.3 billion to MNT 3,724.9 billion, an increase of 44.8 percent that outstripped revenue growth by 14 percentage points. Net profits fell by 12 percent from MNT 831.2 billion in 2022 to a low of MNT 578.5 billion in 2024, before partially recovering to MNT 756.7 billion in 2025. This was nevertheless still 9 percent below the level of profit realized in 2022. 2025's profit of MNT 2,309.4 billion was

the highest budget contributor as well, reflecting its position as the year with the highest revenue. This fact has helped mask EMCG's deteriorating cost structure and explain why efforts to address it have been somewhat lackadaisical. Understanding where along the cost structure increases are taking place will allow for more pointed solutions. The EMC General Director's public disclosures and MONTSAME reporting identify three primary cost escalation sources. First, electricity tariff increases of 37 percent since November 2022 raised the energy cost of ore crushing, grinding, and flotation - energy-intensive processes that account for approximately 35 to 40 percent of total processing costs in comparable porphyry copper operations. Second, the declining ore grade described in Chapter 4.1 requires processing progressively more ore to yield a tonne of concentrate, directly increasing variable operating costs per tonne of output. Third, the deepening open pit increases haulage distances for ore and waste rock within the mine, raising fuel consumption and equipment wear costs per tonne mined. These three drivers are structural rather than cyclical: electricity prices are unlikely to fall significantly given Mongolia's infrastructure constraints, ore grade will continue declining, and pit depth will continue increasing. This means the cost escalation trend will persist and potentially accelerate unless offset by revenue-side improvements - higher volumes, higher prices, or higher product value - of the kind targeted by the optimization scenarios in Chapter 5.

4.3 Per-Tonne Efficiency Analysis

Converting the aggregate financial data to per-tonne metrics reveals the efficiency dynamics obscured by aggregate revenue growth. Table 4.2 presents per-tonne indicators in MNT million per tonne and their USD equivalents using annual exchange rates.

Table 4.2: Per-Tonne Financial Indicators (MNT million/tonne and USD/tonne)

Indicator (MNT million/t)	2022	2023	2024	2025
Revenue per tonne	5.987	6.672	6.995	8.507
Cost per tonne	4.109	4.833	5.541	6.482
Profit per tonne	1.328	1.331	1.018	1.315

Indicator (MNT million/t)	2022	2023	2024	2025
Budget contribution per tonne	2.847	3.351	2.725	4.016
Indicator (USD/tonne — approx.)	2022	2023	2024	2025
Revenue per tonne	\$1,906	\$1,925	\$2,063	\$2,400
Cost per tonne	\$1,308	\$1,393	\$1,636	\$1,829
Profit per tonne	\$423	\$384	\$300	\$371

The disconnect couldn't be greater. Revenue per tonne grew 42.1 percent from 2022 to 2025. Cost per tonne grew 57.8 percent over that time. Profits per tonne fell from MNT 1.328 million (USD 423) in 2022 to MNT 1.315 million (USD 371) in 2025, roughly flat in tugrugs and materially negative in dollars due to tame depreciation of the tugrug. The MNT 1.018 million (USD 300) per tonne bottom in 2024 shows how susceptible the project is to downside if copper prices come down against a backdrop of continuing cost inflation.

To provide some perspective on these numbers, it is helpful to compare EMC's per tonne cost structure to other copper concentrate producers. The CRU Copper Mining Cost Service [16] monitors cash costs for the worldwide copper mining industry on a per pound of payable copper basis. At 22.5 percent concentrate grade and 2025 dollar/tugrug exchange rate, EMC's total cost of production of roughly MNT 6.482 million (USD 1,862) per tonne of concentrate equates to an all-in sustaining cost of about USD 1.95 per pound of payable copper. This would put EMC in the 2nd quartile of the global copper cost curve and far below the estimate provided by EMCI management. However, that positioning would fall to the 3rd quartile of the cost curve if costs were to rise as they have during 2022-2025. First-quartile producers such as KGHM Polska Miedź in Poland and Freeport-McMoRan's Grasberg mine in Indonesia achieve all-in sustaining costs of USD 1.20 to 1.60 per pound, largely through higher ore grades, lower logistics costs relative to revenue, and integrated smelting operations that eliminate TC/RC charges. EMC's logistics cost component represents approximately 18 to 22 percent of total operating cost per tonne of concentrate, based on disaggregated cost reporting in the CAREC analysis and publicly disclosed UBTZ tariff

schedules. At USD 1.07 billion in 2025 total operating costs, a 20 percent logistics share implies approximately USD 214 million in annual logistics expenditure - representing the primary target of the Phase 1 and Phase 2 optimization measures analyzed in Chapter 5.

Cost per tonne increased continuously across every year of the study period, from MNT 4.109 million in 2022 to MNT 6.482 million in 2025. The sources of this pressure include declining ore grade requiring more ore to be processed per tonne of concentrate, rising electricity prices (a 37 percent increase since November 2022 per the EMC General Director's 2023 statement [19]), and extended haulage distances within the open-pit mine as the pit deepens. These findings confirm that cost escalation rather than revenue instability is the dominant driver of declining operational efficiency.

Interpretation

The flat profit-per-tonne trajectory is diagnostic of a system that is consuming efficiency gains from favorable copper prices rather than accumulating them. In other words, the operation is running faster to stay in place. The optimization measures analyzed in Chapter 5 target both the cost side - through logistics efficiency - and the revenue side - through volume expansion and product value uplift.

4.4 Border Node Cycle Time Analysis

Empirical data from CAREC Rail Transport Analysis and corroborating sources provide a disaggregated picture of border dwell time at Zamyn-Uud/Erenhot. Table 4.3 presents the typical time breakdown for a loaded copper concentrate train of 40 wagons carrying approximately 3,500 tonnes.

Table 4.3: Border Dwell Time Disaggregation - Zamyn-Uud/Erenhot

Process Step	Duration (hrs)	Type	PCE Contribution
Arrival and entry to Mongolian customs zone	1.5	NVAT	0%
Mongolian customs documentation processing	11.5	NVAT	0%
Technical rolling stock inspection	1.0	NVAT	0%

Process Step	Duration (hrs)	Type	PCE Contribution
Bogie exchange (gauge change)	3.0	VAT	9.4%
Transfer to Chinese zone	0.5	NVAT	0%
Chinese customs documentation processing	15.0	NVAT	0%
Wagon shortage waiting time	7.5	NVAT	0%
TOTAL DWELL TIME	~32 hrs (range: 27–37)		PCE = 9.4%

The figures confirm that Process Cycle Efficiency is 9.4 percent [4] - meaning that for every 32 hours a train spends at the border, only 3 hours contribute any physical value. The remaining 29 hours are spent waiting, queueing, or being processed through administrative procedures that could largely be completed before the train arrives. The Chinese customs documentation step alone (15 hours average) exceeds the entire value-added portion by a factor of five. This reinforces the identification of the border node as the primary system constraint within the TOC framework.

The wagon shortage delay of 7.5 hours is notable because it is entirely independent of document processing. Even if customs clearance were instantaneous, this delay would still impose additional dwell time - making it a separate bottleneck that requires a separate physical solution.

4.5 Fiscal Burden and State Revenue Distribution

Mongolia's mining fiscal regime creates an unusually high effective tax burden relative to accounting net profit. Table 4.4 documents the relationship between state budget payments and corporate financial performance.

Table 4.4: Fiscal Burden Ratios, 2022–2025

Fiscal Ratio	2022	2023	2024	2025
Cost share (C/R × 100)	68.7%	72.5%	79.3%	76.2%

Fiscal Ratio	2022	2023	2024	2025
Net profit margin (P/R × 100)	22.2%	20.0%	14.6%	15.5%
State payments / Revenue (B/R × 100)	47.6%	50.3%	39.0%	47.2%
State payments / Net Profit (B/P × 100)	214%	252%	268%	305%

4.6 Summary of Baseline Inefficiencies

EMC's total cost of approximately USD 1,829/tonne places it in the second quartile of global copper mining cost curve, but cost escalation during 2022-2025 would place it in the third quartile if trends continue. First-quartile producers achieve USD 1.20-1.60 per pound largely through higher ore grades, lower logistics costs, and integrated smelting operations. EMC's logistics costs represent approximately 20 percent of operating costs, or USD 214 million annually-the primary target of Phase 1 and Phase 2 optimization.

- Per-tonne operating costs increased 57.8 percent from 2022 to 2025 while profit per tonne fell in real terms, indicating structural cost escalation exceeding revenue growth.
- The border interchange node imposes 27 to 37 hours of dwell time per train, with a Process Cycle Efficiency of 9.4 percent - the dominant source of logistics waste in the system.
- Customs documentation accounts for 26.5 hours of the dwell time - 83 percent of non-value-added time - and is addressable through information technology and procedural reform.
- Wagon shortage at Erenhot adds 7.5 hours independently of documentation processing, requiring a physical logistics solution.
- The Ulaanbaatar urban corridor reduces mainline velocity and constrains system capacity, preventing EMC from expanding throughput even if mine production increases.
- Low product value density means 430,000 tonnes of gangue and moisture travel the full 1,400 kilometers annually, amplifying the financial impact of every delay.

- The state captures over 300 percent of accounting net profit in fiscal charges, creating a governance structure in which operational optimization is not merely desirable but fiscally critical to sustaining Mongolia's national budget.

Chapter 5: Engineering Optimization Scenarios

5.1 Phase 1 - Process Automation and Information Flow Integration

The EDI pre-clearance workflow submits electronic manifests 48 hours before departure. Risk-assessment algorithms evaluate shipments while trains transit the 1,400-kilometer corridor. Upon arrival at Zamyn-Uud, Non-Intrusive Inspection X-ray portals compare scanner imagery against electronic manifests, with data transmitted simultaneously to Erenhot customs. Expected dwell time reduction: from 32 hours to 5-6 hours (85 percent improvement). China Railway Hohhot Group confirmed in July 2025 that inspection times at Erenhot had already been reduced to under 30 minutes for pre-cleared shipments.

The EDI pre-clearance workflow leverages the China-Mongolia Joint Customs Control framework to shift customs processing from sequential post-arrival review to parallel pre-arrival risk assessment. The operational sequence is as follows.

Forty-eight hours before scheduled departure from the Erdenet concentrate stockpile, EMC's logistics team submits a standardized 18-field electronic manifest through the JCC Single Window portal. The manifest includes train identification, individual wagon numbers, declared gross and net weights per wagon, HS commodity code 2603.00 for copper concentrate, origin mine identification, consignee smelter, independent assay certificate results showing copper grade and impurity profile, and export license reference.

While the train travels the 164-kilometer spur to Darkhan and then south through Ulaanbaatar to Zamyn-Uud, a journey of approximately two days, risk-assessment algorithms on both the Mongolian and Chinese customs systems evaluate the shipment against declared parameters and historical data. EMC's long export history as a state-owned enterprise with 46 years of continuous operations positions it for automatic low-risk classification under both regimes.

Upon arrival at Zamyn-Uud, the train passes through a Non-Intrusive Inspection X-ray portal at rolling speed. Scanner imagery is compared automatically against the pre-submitted electronic manifest, and X-ray data and weighbridge readings are transmitted simultaneously to Erenhot customs. The shipment is released for bogie exchange without manual document review.

The result is an expected reduction in border dwell time from 32 hours to 5 to 6 hours, an 85 percent improvement. Of the remaining time, 1.5 hours represents unavoidable entry and transfer procedures, and 3.0 hours represents the bogie exchange operation itself.

Current progress

As of July 2025, China Railway Hohhot Group confirmed that inspection time at Erenhot had already been reduced to under 30 minutes for pre-cleared shipments, and that a full digital port system enabling complete paperless clearance was under development. The Mongolia Customs Modernization Programme, funded by a MNT 4.5 billion soft loan, is constructing a One Stop Customs Center at Zamyn-Uud expected to reduce clearance delays by 30 percent.

5.1.2 Authorized Economic Operator Certification

AEO status is a bilateral trade facilitation certification recognizing businesses that demonstrate sustained compliance with customs regulations, supply chain security standards, and transparent record-keeping. EMC is an ideal candidate: a 100 percent state-owned enterprise with audited financials reviewed by KPMG since 2022 and 46 years of uninterrupted export history.

The certification process requires submission of a self-assessment questionnaire, a physical on-site validation audit by Mongolian Customs, and mutual recognition with Chinese Customs under the existing bilateral AEO framework. Once certified, EMC's export shipments would receive guaranteed green-channel processing at every crossing, regardless of inspector availability or inspection cycle timing. This converts the current probability-based fast-lane benefit of EDI pre-clearance into a contractual guarantee.

5.1.3 Dedicated Unit Train Scheduling on the Erdenet Spur

The Erdenet-Darkhan spur currently operates without a fixed freight timetable. EMC's concentrate trains depart when loading is complete and a locomotive is available, creating departure variability of up to 48 hours around any planned schedule. This variability propagates downstream: later departure means later arrival at Zamyn-Uud, potentially missing favorable inspection windows and extending total cycle time. The quantitative impact of scheduling variability is more significant than it might initially appear. When a train arrives at Zamyn-Uud outside a pre-agreed crossing window, it joins a general queue that may include coal, general cargo, and other freight trains competing for the limited number of daily bogie exchange slots at Erenhot. During peak periods, particularly August through October, when agricultural commodity exports coincide with the heavy mining season, queue times of 12 to 18 hours beyond the standard dwell time have been documented. Fixed-window scheduling under a formal UBTZ priority freight agreement would guarantee

a specific arrival window at Zamyn-Uud within a tolerance of plus or minus four hours, enabling pre-assignment of a specific bogie exchange slot and pre-positioning of Chinese wagons timed to the expected completion of the exchange operation. The financial benefit of this alone, independent of EDI pre-clearance, is estimated at USD 1.0 million per year in base case through reduction of queue-related delays, faster wagon cycle time, and marginally reduced fuel costs from more predictable locomotive operations.

The proposed optimization is a negotiated priority freight scheduling agreement with UBTZ establishing fixed departure windows for loaded southbound trains and corresponding empty return windows for northbound movements. This is a contractual and operational arrangement requiring no capital expenditure. Analysis of comparable mining rail spurs in comparable operating environments suggests that fixed scheduling reduces origin-to-border transit time variability by 60 to 80 percent and average transit time by 15 to 25 percent.

5.1.4 Chinese-Gauge Wagon Pre-Positioning at Erenhot

The 7.5-hour wagon shortage delay at Erenhot is a physical logistics constraint entirely independent of document processing speed. The solution is a dedicated wagon pool agreement with China Railway Hohhot Group. Under this arrangement, a fleet of Chinese standard-gauge ore wagons sized to match EMC's weekly crossing schedule would be pre-positioned at Erenhot on a standing basis. The wagon pool would be restocked after each loaded crossing by the return of empty wagons.

This arrangement effectively converts the wagon availability constraint from an unpredictable queue into a planned operational step. Combined with EDI pre-clearance, the resulting optimized crossing sequence collapses from 32 hours to 5 to 6 hours. These measures represent low-capital, high-impact interventions that can be implemented within existing institutional frameworks.

5.2 Phase 2 - Infrastructure Debottlenecking

5.2.1 Bogdkhan Railway Bypass

The Bogdkhan Railway Bypass (BRB) is a railway alignment stretching 144.9 km [10] from Rashaant station north of Mongolia's capital city Ulaanbaatar all the way down to Maanit station south of Mongolia's capital. The new railway bypasses Ulaanbaatar completely. Groundbreaking of the project started in July of 2022. The new railway contains 14.6 km of tunnels [10] and 4.77 km of viaduct structures. It is considered to be the most technically

challenging railway construction project Mongolia has ever seen. Completion is estimated for November 2026 at a total project investment of approximately MNT 1.2 trillion.

For EMC's copper concentrate movements, the bypass provides two distinct benefits. The primary benefit is transit time reduction: eliminating urban speed restrictions and level crossing stops reduces Ulaanbaatar transit time by 4 to 6 hours per train. The secondary and more financially significant benefit is system capacity expansion: the bypass adds 5 to 6 million tonnes of annual freight capacity to the Trans-Mongolian corridor, unlocking headroom for EMC to increase shipment frequency from 164 to approximately 185 train movements per year.

This capacity expansion, combined with the ore processing capacity growth already underway at the mine, enables a 13 percent volume increase in concentrate throughput, from 574,987 tonnes in the 2025 baseline to approximately 649,000 tonnes annually. As of April 2026, the bypass is approximately 70 percent complete [21]. Track-laying is underway on completed earthworks sections. Tunneling, which encountered variable geological conditions causing earlier delays, is progressing on remaining sections. The engineering significance of the bypass extends beyond the headline capacity and time savings figures. The current routing of all Trans-Mongolian Railway traffic through Ulaanbaatar creates a structural fragility in Mongolia's export logistics system: any disruption to urban railway operations, whether from accidents, maintenance requirements, or adverse weather events, halts all north-south freight movements simultaneously. The bypass provides route redundancy that eliminates this single point of failure, converting the current serial system architecture into a parallel one where bypass and urban routing can complement each other. For EMC's concentrate movements specifically, the bypass enables routing optimization based on real-time traffic conditions: under normal operations, all concentrate traffic would use the bypass to avoid urban delays; under bypass maintenance windows, the urban corridor serves as a failover route. The financial model treats the 13 percent volume expansion as the primary benefit of the bypass, but the resilience value of route redundancy, estimated at approximately USD 3.3 million per year based on a 10 percent annual probability of a significant disruption event lasting an average of 10 days, is an additional benefit that is excluded from the conservative and base-case EBITDA uplift figures in Table 6.1 and should be considered additive to the reported estimates. The bypass also has positive externalities for Ulaanbaatar's urban environment. The removal of through-freight from the urban corridor eliminates approximately 37,000 daily heavy truck equivalents of

urban rail traffic disruption at level crossings, improving road traffic flow and reducing vehicle emissions from trucks idling at closed crossings. While these externalities are not captured in EMC's financial model, they constitute a portion of the social return on the bypass investment that justifies government prioritization and accelerated completion.

5.2.2 Khangai-Mandal Secondary Corridor

Operational since November 2022, the Zuunbayan-Khangai railway offers a second railway line from Mongolia's interior regions to China through the Khangai-Mandal border. Transporting Erdenet-origin copper concentrate through Khangai is around 300-400 kilometres longer than through Route 1 and is estimated to increase rail freight costs by USD 3-8/tonne. This makes Khangai uneconomical as a primary export route.

The strategic value of Khangai is as a contingency corridor. During the 2021-2022 COVID disruption, the Erenhot rail port was closed for approximately six weeks, halting EMC's exports entirely. A pre-established diversion capability via Khangai would have allowed approximately 60 percent of weekly volume to continue moving with 48 hours' notice. Maintaining this capability, through periodic trial shipments, standing customs relationships, and pre-positioned logistics agreements, has an annual expected value of USD 3.1 million based on a 10 percent annual disruption probability.

5.2.3 Permanent 24-Hour Border Crossing

The 24-hour crossing pilot demonstrated that distributing freight crossings across all hours of the day significantly reduces peak-hour queuing. EMC's copper concentrate trains, which carry no perishable cargo and require no special handling beyond commodity inspection, are ideal candidates for off-peak overnight routing. EMC would have crossings timed between 02:00 and 08:00 local time under a permanent 24-hour operation, when activity at the Erenhot processing zone is less affected by other flows of coal, iron ore and consumer products. The smelter investment addresses the core problem of EMC's current system: shipping low-density intermediate material over 1,400 kilometers to Chinese processors who capture value. Three advantages: (1) permanently eliminates Treatment and Refining Charges (USD 23-45 million annually), (2) reduces annual tonnage from 574,000 tonnes concentrate to 124,000 tonnes cathode (78 percent reduction, USD 36M logistics saving), and (3) sells standardized commodity at LME spot prices to global buyers rather than accepting Chinese monopsony pricing on concentrate.

5.3. On-Site Smelter Integration

5.3.1 Strategic Rationale

The smelter investment addresses the fundamental product architecture problem of the current system: EMC ships low-density, discounted intermediate material over a long distance to Chinese processing facilities that capture a significant share of the value chain. The smelter inverts this structure by capturing the processing margin domestically and shipping a high-density, premium-priced final product.

Three structural advantages drive the case for the smelter. First, it permanently eliminates Treatment and Refining Charges. Under normalized market conditions of USD 40 to 50 per tonne, these charges cost EMC USD 23 to 29 million annually. At historical peak levels of USD 80 per tonne, the cost exceeds USD 45 million. Second, it decreases annual tonnage required for transport by nearly 78 percent from 574,000 tonnes of concentrate to around 124,000 tonnes of cathode. This alone decreases logistics expenditures by USD 36 million every year. Third, copper cathode is traded internationally as a standardized commodity and can be sold for essentially the LME spot price. Looking at Canada and Korea alone, this allows Mongolian entities access to downstream buyers in Japan, South Korea, Europe, and North America through TMDL, which when fully built-out will link Mongolia to nearly 500 ports around the world [22]. A fourth advantage worth highlighting independently is related to buyer diversification and negotiating power with regards to price. As a concentrate exporter, EMC sells exclusively to Chinese smelters, which have historically used their monopsony position to negotiate TC/RC rates above global benchmarks during periods of surplus concentrate supply. As a cathode producer, EMC would sell a standardized LME, registered product to a globally competitive buyer pool. Even if cathode is sold through Chinese trading intermediaries, the existence of alternative buyers creates competitive tension that limits the discount any single buyer can impose. Market analysis by CRU Group suggests that Mongolian LME-grade copper cathode would carry a premium of USD 50 to 80 per tonne over LME settlement in Asian physical markets given its geographic proximity to Chinese and Korean manufacturing demand centers, an additional revenue benefit of approximately USD 6 to 10 million per year not captured in the base-case DCF model. A fifth consideration is Mongolia's industrial development policy. The Mongolian government has explicitly stated its objective of increasing domestic value addition in mineral exports as part of its Vision 2050 long-term development program. A fully operational copper smelter at Erdenet would position Mongolia as a cathode-producing nation, with downstream

implications for the development of copper fabrication capacity, wire rod, tube, and sheet production, that could further extend the domestic value chain over a multi-decade horizon. These strategic and policy considerations reinforce the financial case for the smelter without being necessary to it: the positive NPV and attractive payback period stand independently of industrial policy objectives.

5.3.2 Process Flowsheet and Mass Balance

The preliminary flowsheet is based on Flash Smelting technology which is the international standard for large-scale copper processing. Mass balance based on annual production of 2025 in tonnes: Of the 574,000 tonnes of concentrate feed (22.5 percent copper, 8 percent moisture, as-received), the drying circuit reduces the moisture content of the concentrate to less than 1 percent before the dried concentrate is fed to the Flash Smelting furnace with oxygen enriched air and silica flux. Matte generated from the Flash Smelting furnace is 65 percent copper and is treated in Peirce-Smith converters to produce blister copper (98.5 percent copper). The anode furnaces refine and cast anodes for electrorefining, which produces LME Grade A copper cathode, 99.99 percent copper. The off-gas from the smelting circuit is routed to a sulfuric acid plant which captures the SO_2 and produces about 450,000 tonnes of acid annually. Copper recovery, from concentrate feed to cathode, is 96.1 percent. Production of cathode is approximately 124,100 tonnes per year. The overall mass reduction factor is 4.6 to 1. For each tonne of copper cathode produced, 4.6 tonnes of concentrate feed is required. Freight volumes decrease from 574,000 tonnes per year of concentrate to 124,100 tonnes per year of cathode.

5.3.3 Capital Expenditure and Project Economics

The CAPEX estimate for a full metallurgical smelter at Erdenet is USD 1.50 to 2.00 billion, with a midpoint estimate of USD 1.75 billion. This is a Class 4 estimate per AACE International classification, with expected accuracy of minus 15 percent to plus 30 percent. A Front-End Engineering Design study is required to refine this to Class 3 accuracy before project sanction. The higher capital intensity compared to African benchmarks reflects Mongolia's inland location, continental climate with winter temperatures below minus 30 degrees Celsius requiring enclosed structures and additional civil works, and the less-developed local construction supply chain.

Table 5.1 presents the Discounted Cash Flow model summary under base-case assumptions of USD 12,000 per tonne LME copper and normalized TC/RC of USD 40 per tonne.

Table 5.1: Smelter Project DCF Summary — Base Case

Parameter	Value
Annual cathode production	124,100 tonnes LME Grade A
LME copper price (base case)	USD 12,000 / tonne
Realized cathode price (97.5% of LME)	USD 11,700 / tonne
TC/RC savings (vs. USD 40/t normalized)	USD 23.0 million / year
Logistics cost saving (78% freight reduction)	USD 36.2 million / year
Annual smelter OPEX	USD 22.3 million (USD 180/t cathode)
Total CAPEX (midpoint)	USD 1,750 million
Annual EBITDA uplift (base case)	USD 150–193 million
Annual D&A (25-year life)	USD 70 million
Net Present Value at 8% real discount rate	USD 850 million (positive)
Break-even LME copper price (zero NPV)	USD 9,500 / tonne
Simple payback (EBITDA basis)	~10.3 years

The NPV stays strongly positive for all considered prices above the break-even price point of USD 9,500/tonne. With LME copper prices ranging between USD 12,000/tonne and USD 14,000/tonne as of this writing, and analyst consensus pointing to persistent structural deficit out through 2030, the margin of safety is comfortable. Negative copper prices are unimaginable. Even at the bear-case copper price of USD 7,500/tonne [23] which (when discussing with the EMC General Director) he claims is the industry-wide floor for operating costs, the smelter NPV would be negative, but few major global copper producers would operate under that scenario either. It is a tail risk, not a planning risk.

Starting with a phased approach of an initially 10,000 tonnes-per-year SX/EW cathode plant (estimated CAPEX USD 60 million, construction timeline 2-3 years) allows for a low-risk, early-revenue precursor project. Running oxide ore and heap leach residues already in stockpile, such a plant would produce roughly USD 117 million/year in revenue at base-case prices versus roughly USD 55 million in value stockpiled today as residue, providing a USD 62 million annual uplift and paying back CAPEX three years after initial expenditure. Furthermore, the SX/EW plant allows SMCC to build smelting-specific operational capability and labor pool before commissioning the larger, metallurgical smelter. This exercise does not take into account limiting factors such as environmental, regulatory and social constraints.

Chapter 6: Financial Impact of Optimization

6.1 Analytical Framework

This chapter integrates the per-optimization financial impacts from the preceding engineering scenarios into a consolidated view of EMC's projected financial performance. The analysis uses the 2025 audited baseline of USD 1,321 million revenue, USD 380 million EBITDA [2], and USD 632 million state budget contribution as the comparison point. Three implementation phases reflect realistic engineering and commercial timelines. All projections use a normalized medium-term LME copper price of USD 12,000 per tonne [24,23] and TC/RC of USD 40 per tonne for post-2027 periods, consistent with analyst consensus for balanced concentrate market conditions. The financial model is constructed as an income statement model rather than a cash flow model. This choice reflects the primary analytical objective of assessing EMC's operational profitability trajectory rather than its investment financing structure. EBITDA is used as the central metric because it is the performance indicator most closely linked to operational decisions, it excludes financing costs, which are determined by capital structure choices outside the scope of this thesis, and excludes depreciation, which is a non-cash charge that does not affect the operational cash generation capacity being optimized. The state budget contribution is modeled as a function of revenue, applying Mongolia's Minerals Law fiscal structure: a 25 percent corporate income tax rate on taxable profit, a 5 percent royalty on gross sales, and a 10 percent windfall profit levy applicable when copper prices exceed USD 2,600 per tonne. Dividends to the state are modeled separately based on the historical pattern of 30 to 40 percent of net profit, which has been the observed payout ratio over the study period. The three-scenario structure (conservative, base-case, optimistic) captures the key uncertainties in each optimization measure without attempting a full probabilistic Monte Carlo simulation. Conservative assumptions apply the lower bound of engineering estimates for efficiency improvements, for example, a 75 percent border dwell time reduction rather than the 85 percent central estimate for EDI pre-clearance. Optimistic assumptions apply the upper bound and include favorable interactions between measures - for example, AEO certification [11] accelerating the EDI rollout timeline. The base-case represents the central engineering estimate from each source and is the scenario used for NPV calculations, income statement projections, and state budget impact assessment.

6.2 Phase-by-Phase EBITDA Uplift

Table 6.1 presents the incremental EBITDA contribution of each optimization measure across conservative, base-case, and optimistic scenarios. The base-case totals show that Phase 1 process measures contribute USD 38 million per year, Phase 2 infrastructure measures contribute USD 52 million per year after ramp-up, and Phase 3 smelter integration contributes USD 237 million per year at steady-state operation. Combined, full system optimization generates USD 327 million of incremental annual EBITDA against the 2025 baseline of USD 380 million - an 86 percent improvement in operational profitability. Phase 1 EBITDA uplift of USD 38 million per year derives from three sources. EDI pre-clearance reduces border dwell time from an average of 32 hours to approximately 5 to 6 hours, cutting per-wagon border costs by USD 8,200 and enabling 19 additional round-trip wagon rotations per year across EMC's operating fleet of 400 wagons. The financial impact is USD 18 million in reduced logistics holding costs and USD 12 million in incremental throughput revenue from faster wagon cycles. Wagon pre-positioning eliminates 7.5 hours of average waiting time caused by Chinese-gauge wagon shortages at Erenhot, contributing an additional USD 5 million in annual efficiency gains. Fixed-interval scheduling reduces mainline variance and opportunistic queue insertion by other freight operators, contributing USD 3 million in reliability-related savings. Phase 2 EBITDA uplift of USD 52 million per year is dominated by the Bogdkhan Bypass's volume expansion effect. The 13 percent throughput increase from 574,987 tonnes to approximately 649,000 tonnes per year adds USD 44 million at base-case copper prices and TC/RC assumptions. The 24-hour border crossing, modeled independently of Phase 1 EDI measures, adds USD 5 million through further congestion reduction and peak-hour avoidance. Spur capacity upgrades contribute USD 3 million through increased train frequency and reduced locomotive idle time. The incremental margin on the additional 74,000 tonnes of concentrate is higher than the blended average because fixed costs are already covered by the baseline volume: the marginal EBITDA per tonne on Phase 2 volume expansion is approximately USD 594, compared to the blended average of USD 661 per tonne on the full optimized volume. Phase 3 delivers the largest but most capital-intensive uplift. The elimination of TC/RC charges at USD 40 per tonne saves USD 23 million annually. The mass reduction from 574,000 tonnes of concentrate to 124,000 tonnes of cathode saves USD 36 million in logistics costs. The value capture from cathode premium pricing over discounted concentrate adds USD 178 million at base-case assumptions. Net of smelter operating costs of USD 140 per tonne of cathode (USD 17.4 million annually for 124,000 tonnes), the aggregate Phase 3 EBITDA contribution is USD

237 million per year, with a simple payback of 10.3 years on the USD 1.75 billion CAPEX investment.

Table 6.1: Cumulative EBITDA Uplift by Implementation Phase (USD million/year)

Optimization Measure	Conservative	Base Case	Optimistic
PHASE 1: Near-Term (0–12 months)			
Dedicated rail spur scheduling	\$0.7M	\$1.0M	\$1.5M
Digital pre-clearance + AEO + wagon pre-positioning	\$4.9M	\$9.3M	\$13.3M
Khangri contingency route (expected disruption value)	\$1.7M	\$3.1M	\$4.4M
TC/RC and price risk management	\$11.8M	\$20.8M	\$31.8M
Phase 1 Total EBITDA Uplift	\$19.1M	\$34.2M	\$51.0M
PHASE 2: Medium-Term (2027)			
Bogdkhan Bypass — volume expansion and scheduling	\$40.1M	\$52.1M	\$68.0M
Permanent 24-hour border crossing	\$1.8M	\$3.3M	\$5.5M
Phase 2 Total Additional EBITDA Uplift	\$41.9M	\$55.4M	\$73.5M
PHASE 3: Smelter (2028–2030)			
Copper smelter — EBITDA uplift from operations	\$120M	\$165M	\$210M
Less: Smelter depreciation (USD 1.75B ÷ 25 years)	(\$70M)	(\$70M)	(\$70M)
Phase 3 Net EBIT Uplift	\$50M	\$95M	\$140M
CUMULATIVE EBITDA UPLIFT (All Phases)	\$181M	\$284M	\$374M

Optimization Measure	Conservative	Base Case	Optimistic
As % improvement over 2025 baseline EBITDA (\$380M)	+48%	+75%	+98%

6.3 Fully Optimized Income Statement (2030 Projection)

Table 6.2 presents the projected income statement for EMC in 2030 under full base-case optimization, compared to the 2025 audited baseline. Revenue increases from USD 1,321 million to USD 1,762 million, driven by the Bogdkhan volume expansion (USD 172 million), smelter value uplift (USD 193 million), and price risk management net benefit (USD 55 million), partially offset by smelter operating costs and logistics cost changes. Several aspects of the 2030 projection merit specific analytical discussion. First, the revenue line understates the total benefit of optimization because the smelter eliminates TC/RC charges that previously reduced realized revenue: under the concentrate sales model, EMC's 2025 realized price was approximately USD 2,298 per tonne of concentrate, representing the LME copper equivalent of USD 10,210 per tonne of contained copper minus TC/RC and moisture deductions. Under the cathode sales model, EMC realizes the full LME price of USD 12,000 per tonne of contained copper less only a modest cathode premium discount to account for delivery logistics. Second, the cost line in 2030 reflects the smelter's operating cost addition of approximately USD 138 million per year, partially offset by logistics savings of USD 36 million from the concentrate-to-cathode mass reduction. The net cost impact of the smelter on the operating cost line is therefore an addition of approximately USD 102 million but this is more than compensated by the USD 363 million revenue uplift from value capture, TC/RC elimination, and volume growth. Third, the 2030 case assumes full ramp-up of all three phases at the same time. In reality, Phase 1 would be fully ramped by 2026, Phase 2 by 2027 (conditional upon completion of the bypass) and Phase 3 would not be expected to come online before 2033, based on typical smelter construction lead times. This means that the 2030 income statement is somewhat misleading as it effectively shows a partial steady-state situation, with Phases 1 and 2 fully embedded in the business but Phase 3 not quite ready (i.e., still in commissioning). As such, we can interpret the USD 707 million EBITDA number shown in Table 6.2 as a realistic near-term EBITDA target, with further upside to USD 707 million + USD 237 million achievable when the smelter is commissioned around 2033–2035. The state budget contribution projection of USD 952 million in 2030 (versus USD 632 million in 2025) reflects the application of Mongolia's existing fiscal framework to the higher pre-tax earnings. This USD 320 million increment represents the single largest fiscal

benefit analysis that could be presented to the Mongolian government in support of accelerated completion of the Bogdkhan Bypass and negotiation of a 24-hour permanent crossing arrangement at Zamyn-Uud/Erenhot.

Table 6.2: EMC Income Statement - 2025 Baseline vs 2030 Fully Optimized (USD million)

P&L Line	2025 Actual	2030 Optimized	Change
Revenue	\$1,321M	\$1,762M	+\$441M (+33%)
Total Operating Costs	\$941M	\$1,054M	+\$113M
EBITDA	\$380M	\$708M	+\$328M (+86%)
EBITDA Margin	28.8%	40.2%	+11.4 percentage points
D&A (incl. smelter)	\$55M	\$125M	+\$70M
EBIT	\$325M	\$583M	+\$258M (+79%)
Income Tax + Royalties	\$244M	\$373M	+\$129M
Net Income	\$81M	\$210M	+\$129M (+159%)
Total State Budget Contribution	\$632M	\$952M	+\$320M (+51%)

6.4 Sensitivity Analysis

The optimization results are robust across a wide range of copper price scenarios. Table 6.3 presents EBITDA uplift under the base-case optimization suite at varying LME prices.

Table 6.3: EBITDA Uplift Sensitivity to LME Copper Price

LME Scenario	Price / tonne	Baseline EBITDA	Optimized EBITDA	Uplift
Bear case (deep recession)	\$7,500	\$186M	\$372M	\$186M
Low base	\$9,000	\$270M	\$507M	\$237M
Base case / current market	\$12,000	\$380M	\$664M	\$284M
Bull case (J.P. Morgan 2026)	\$14,000	\$432M	\$716M	\$284M

A key finding from the sensitivity analysis is that Phase 1 and Phase 2 optimization benefits are largely price-insensitive, as they derive from logistics cost savings, risk reduction, and process efficiency rather than commodity price exposure. Even at the USD 7,500 bear-case price, the stated industry operating cost floor, the optimized EMC generates USD 186 million more EBITDA than the unoptimized baseline. This means that supply chain optimization is not merely a fair-weather strategy but a structural resilience measure that reduces vulnerability to copper price cycles. This demonstrates that the proposed optimization strategy enhances both profitability and resilience under varying market conditions.

Chapter 7: Conclusions and Engineering Recommendations

7.1 Summary of Key Findings

This thesis has characterized the Erdenet Mining Corporation export logistics system through quantitative analysis of audited financial data, empirical border performance metrics, and engineering scenario modeling. The study was structured around four research questions, each of which the analysis has addressed with empirical evidence and quantified engineering estimates. The answers to each research question are summarized in turn before the cross-cutting conclusions are drawn.

RQ1 asked: what are the primary bottlenecks limiting throughput in EMC's export logistics system? The analysis in Chapter 4.4 identified the Zamyn-Uud/Erenhot border interchange node as the unambiguous primary system constraint in the TOC framework, with a Process Cycle Efficiency of 9.4 percent and average dwell time of 32 hours per train crossing. This finding is consistent with Goldratt's [8] prediction that any system with a throughput-limiting constraint will demonstrate characteristic symptoms: inventory accumulation upstream, underutilization of downstream assets, and high variability in total cycle time propagating from the constrained node. All three symptoms are present at Zamyn-Uud/Erenhot. The customs documentation sub-process, consuming 15 hours on average, accounts for 46.9 percent of total dwell time and is the single highest-value target within the constraint node, consistent with the principle established by Hines and Rich [25] that waiting time is the most prevalent and largest category of logistics waste. A secondary bottleneck exists on the Erdenet-Darkhan spur in the form of scheduling unpredictability and passing loop constraints that create variability in train arrival times at Zamyn-Uud, compounding the border node delays by preventing pre-positioning of Chinese wagons and customs personnel.

RQ2 asked: how can process and infrastructure interventions reduce cycle time and improve system efficiency? Chapter 5 identified a three-phase intervention sequence. Phase 1 measures, EDI pre-clearance, AEO certification, wagon pre-positioning, and fixed-interval scheduling, address the border constraint directly with minimal capital expenditure, reducing average dwell time from 32 hours to approximately 5 to 6 hours and improving Process Cycle Efficiency from 9.4 percent to approximately 47 percent. Phase 2 measures, Bogdkhan Bypass and 24-hour border operation, address the mainline capacity constraint and expand system throughput by 13 percent. Phase 3 smelter integration eliminates the need to transport low-value concentrate by converting it to high-value cathode at the mine site, reducing freight volume by 78 percent and qualitatively transforming EMC's commercial

position from a concentrate seller to a refined metal producer. This phased sequence follows the TOC five-step focusing methodology: Phase 1 exploits the existing constraint; Phase 2 elevates the mainline constraint that becomes binding once the border constraint is resolved; and Phase 3 changes the nature of the system so comprehensively that the constraint analysis must be repeated from first principles for the cathode-producing entity.

RQ3 was: what is the economic impact of proposed optimization measures? Through financial analysis detailed in Chapter 6, the cumulative base-case EBITDA uplift of USD 327 million per annum represents the economic improvement under full optimization; this is an improvement of 86 percent over the 2025 base-case of USD 380 million. Contribution to state budget would rise from USD 632 million in 2025 to USD 952 million per annum under full Phase 1 and Phase 2 optimization, an increase of USD 320 million per annum, the economic return on the enabling infrastructure investment spend assessed in this report. RQ4 was: which combination of optimization measures provides greatest overall system and financial benefit? No stand-alone measure provides greater benefit; rather, the suite of measures to be implemented across each of the three phases are complementary and mutually reinforcing. Phase 1 delivers the highest return on investment (USD 38 million incremental EBITDA for minimal capital outlay), Phase 2 enables volume growth that multiplies Phase 1 benefits across a larger throughput base, and Phase 3 transforms the value proposition of the entire system. The optimal combination is the full three-phase sequence implemented in order, with Phase 1 initiated immediately, Phase 2 completed by 2027 aligned with Bogdkhan Bypass commissioning, and Phase 3 sanctioned following completion of a Front-End Engineering Design study and identification of a strategic technology partner.

The baseline system is performing below its structural potential. Per-tonne operating costs increased 57.8 percent from 2022 to 2025, outpacing revenue per tonne growth of 42.1 percent, resulting in a flat or declining profit per tonne trajectory despite the strongest copper price environment in recent history. The cost-to-revenue ratio peaked at 79.3 percent in 2024 before improving modestly to 76.2 percent in 2025.

The Zamyn-Uud/Erenhot border interchange node is the primary system bottleneck, imposing 27 to 37 hours of dwell time per train movement with a Process Cycle Efficiency of 9.4 percent. Customs documentation accounts for 26.5 hours of this dwell time, representing the highest-value target for process improvement. Wagon shortage at Erenhot adds a further 7.5 hours independently of documentation processing.

Phase 1 optimization, electronic data interchange pre-clearance, Authorized Economic Operator certification, dedicated spur scheduling, and wagon pre-positioning, generates an estimated USD 34 million in incremental annual EBITDA under base-case assumptions. These measures are within EMC's operational control, require no major capital expenditure, and should be initiated immediately.

Phase 2 optimization centered on the Bogdkhan Railway Bypass, scheduled for commissioning in November 2026, generates an estimated USD 55 million in additional annual EBITDA by enabling a 13 percent volume increase and reducing transit time. This represents the most significant near-term infrastructure lever available.

Phase 3 the on-site copper smelter, generates USD 95 million in additional annual EBIT after depreciation under base-case assumptions, with a project NPV of USD 850 million at 8 percent real discount rate. The break-even LME copper price of USD 9,500 per tonne provides substantial margin relative to current and projected market levels. The smelter is the transformative investment that repositions EMC from a price-taking concentrate exporter to a refined metal producer at the top of the copper value chain.

Full implementation of all three phases increases EMC's annual state budget contribution from USD 632 million to USD 952 million, an increment of USD 320 million per year representing approximately 3.4 percent of Mongolia's GDP. This figure illustrates that logistics and industrial policy optimization at a single state-owned enterprise can constitute macroeconomic policy.

7.2 Implementation Roadmap

The recommended implementation sequence is structured in four time horizons:

Immediate Actions (0–6 months)

- Configure EMC logistics software to generate the 18-field electronic manifest for JCC pre-clearance submission 48 hours before departure.
- Submit application for Authorized Economic Operator status with Mongolian Customs General Administration.
- Optimization results are robust across copper price scenarios. Phase 1 and Phase 2 benefits derive from logistics efficiency and process improvements rather than commodity price exposure. Even at the USD 7,500 bear-case price (the industry operating cost floor), full optimization generates USD 186 million more EBITDA

than baseline, demonstrating that supply chain optimization is a structural resilience measure reducing vulnerability to copper price cycles.

- Initiate discussions with China Railway Hohhot Group regarding dedicated Chinese-gauge wagon pool at Erenhot.

Short-Term Actions (6–18 months)

- Complete testing and operationalize EDI pre-clearance for all export shipments; verify AEO mutual recognition with Chinese Customs.
- Support government diplomatic efforts to secure permanent 24-hour border crossing arrangements.
- Develop and test contingency routing protocols for Khangai-Mandal diversion, including standing customs pre-clearance with Mandal port authority.
- Engage Ministry of Finance on implementation of a price floor clause requirement in future offtake contract renewals.

Medium-Term Actions (18–36 months)

- Engage UBTZ and Railway Authority of Mongolia on freight slot allocation for the Bogdkhan Bypass corridor upon commissioning.
- Recommended implementation follows four time horizons: immediate actions (EDI, AEO certification, spur scheduling), short-term (operationalize pre-clearance, 24-hour crossing, contingency routing), medium-term (Bogdkhan Bypass integration, smelter FEED study, financing development), and long-term (phased smelter construction, cathode market access, stabilization reserve).
- Develop financing structure for smelter including assessment of multilateral development bank participation, strategic industrial partner equity, and government guarantee mechanisms.

Long-Term Actions (3–10 years)

- Construct initial 10,000 tonne per year SX/EW cathode plant as risk-reduction precursor; commission by 2027–2028.
- Select strategic smelter partner from ongoing tender process; begin full metallurgical smelter construction by 2027.

- Coordinate with Tianjin-Mongolia Dongjiang Logistics Park for cathode storage, shipping, and market access protocols for non-Chinese buyers.
- Develop stabilization reserve from peak-year budget contributions to smooth fiscal impact of copper price cycles.

7.3 Implications for Mongolian Industrial and Fiscal Policy

The fiscal regime analysis reveals a structural tension between short-term state revenue maximization and the long-term investment capacity of the enterprise. When state payments represent 305 percent of net profit, the enterprise retains minimal retained earnings for capital reinvestment, risk absorption, or operational improvement. A stabilization reserve mechanism, redirecting a portion of peak-year budget contributions into a dedicated fund rather than current expenditure, would smooth fiscal revenues and reduce vulnerability to copper price cycles without reducing long-term budget receipts.

The positive NPV and strategic logic of the smelter support government policies that incentivize downstream mineral processing within Mongolia. The government's ongoing partner selection process, which as of January 2025 had attracted interest from 55 companies across 20 countries, represents the most consequential industrial policy decision of the current decade. The selection criteria should weight technological capability, financing strength, and cathode market access alongside equity contribution, to maximize EMC's value-chain positioning rather than minimize short-term capital outlay.

7.4 Limitations and Future Research

This analysis relies on aggregated annual financial data and empirical border performance estimates from published sources. Access to higher-frequency operational data, locomotive tracking records, per-crossing time logs, and wagon cycle data, would enable more precise bottleneck quantification and dynamic modeling. Several specific limitations warrant acknowledgment. First, the border dwell time data from the CAREC Rail Transport Analysis (2020) are now six years old and may not fully reflect operational changes implemented during the 2024 24-hour crossing pilot or the 2025 digital port system developments at Erenhot. Updated empirical measurement of actual dwell times under current operational conditions would strengthen the baseline characterization in Chapter 4.4 and provide a more precise starting point for Phase 1 optimization impact estimation. Second, the financial model treats UBTZ freight tariffs as held constant at 2025 levels. In practice, UBTZ has implemented tariff increases in each of the past four years, and further increases are probable as the company seeks to finance its share of the infrastructure investment required

to accommodate Bogdkhan Bypass traffic. A dynamic model incorporating tariff escalation scenarios would provide a more conservative lower bound for the Phase 2 EBITDA uplift estimate. Third, the smelter CAPEX estimate is a Class 4 engineering estimate with an accuracy range of minus 15 to plus 30 percent. At the plus 30 percent bound, total CAPEX of USD 2,275 million increases the simple payback period from 10.3 to approximately 13 years and reduces the base-case NPV by approximately USD 290 million, still positive but with a reduced margin of safety. A Front-End Engineering Design study, which would deliver Class 3 accuracy (minus 10 to plus 15 percent), is an essential next step before project sanction. Fourth, this thesis does not model the interaction effects between optimization phases. In practice, Phase 1 measures that increase throughput will also increase UBTZ mainline utilization, potentially bringing forward the point at which the mainline itself, rather than the border node, becomes the binding constraint. A discrete-event simulation model would capture these dynamic interactions and identify the sequence and timing of interventions that maximizes cumulative benefit over the implementation horizon. Future research directions include: comparative case analysis of Phase 1 trade facilitation measures across multiple Mongolia border crossings to establish whether the estimated dwell time reductions are consistent across crossing types; longitudinal tracking of EMC's per-tonne cost trajectory post-2025 to validate the structural cost escalation thesis; and a full environmental impact assessment of the proposed smelter, encompassing sulfuric acid marketing strategy, SO₂ emissions management under Mongolian environmental regulations, and water consumption in the semi-arid Orkhon Valley environment.

The financial model is deterministic. Future research should develop a discrete-event simulation model of the Erdenet export logistics system capturing stochastic variability in border queue times, train departure delays, and commodity prices. Software environments such as AnyLogic or Arena would be suitable platforms for this extension.

The environmental and social dimensions of the smelter project are outside the scope of this engineering analysis but constitute a necessary component of a full feasibility assessment. Sulfuric acid disposal, SO₂ emissions management, and labor force expansion in Erdenet city each require dedicated analysis before project sanction.

Finally, this optimization framework could be extended to encompass the broader Mongolian mineral export supply chain, incorporating coal from Tavan Tolgoi, copper from Oyu Tolgoi, and iron ore from Tumurtei, to identify system-level optimization opportunities across the national export logistics network.

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Appendix A: Key Assumptions Summary

Table A.1: All Financial Model Parameters

Parameter	Value Used	Source
MNT/USD exchange rate (2025)	3,481 MNT/USD	Bank of Mongolia annual avg.
2025 total revenue	MNT 4,890.5bn = \$1,404M	EMC official statement
2025 budget contribution	MNT 2,309.4bn = \$663M	EMC official statement
2025 copper concentrate output	574,987 tonnes	EMC official statement
Copper grade in concentrate	22.5%	EMC General Director, 2023
LME copper price (base case)	\$12,000 / tonne	J.P. Morgan 2026 forecast
TC/RC normalized (post-2027)	\$40 / tonne concentrate	Fastmarkets, industry consensus
2026 benchmark TC/RC	\$0 / tonne	Antofagasta-China agreement
Copper payability	96.5%	Industry standard
Cathode price vs LME	97.5% of LME	Industry standard, Grade A
Corporate income tax rate	25%	Mongolia Minerals Law
Royalty rate	5% of gross sales	Mongolia Minerals Law

Parameter	Value Used	Source
Smelter CAPEX (midpoint)	\$1,750M	Class 4 estimate, benchmarks
Smelter OPEX	\$180/tonne cathode	CRU Copper Smelter Cost Database
Project life (smelter)	25 years	Industry standard
Discount rate (NPV)	8.0% real	Sovereign-backed project benchmark
Volume expansion (Bogdkhan base)	13% = 74,620 additional tonnes	Model assumption
Disruption probability (annual)	10%	Based on 2021-22 COVID closure
Working capital cost of capital	9% per annum	Mongolia sovereign borrowing rate

Appendix B: Border Crossing Time Detail

The following sequence describes a representative copper concentrate train crossing at Zamyn-Uud/Erenhot under current (baseline) conditions, based on CAREC Rail Transport Analysis 2020 data and corroborating industry sources.

Day 1, 08:00 — Train of 40 wagons (payload approximately 3,500 tonnes) arrives at Zamyn-Uud station. Entry processing to Mongolian customs zone and wagon positioning in arrival yard: 1.5 hours.

Day 1, 09:30 — Mongolian customs documentation commences. Manual review of paper manifests, cross-referencing with weighbridge data from border scale, stamping of export certificates. Average processing time: 11.5 hours.

Day 1, 21:00 — Mongolian documentation complete. Technical rolling stock inspection: 1.0 hour.

Day 1, 22:00 — Train moves to bogie exchange facility. Bogie exchange on full consist using hydraulic jack sets: approximately 3.0 hours with two jack sets operating in parallel.

Day 2, 01:00 — Bogie exchange complete. Transfer to Chinese zone: 0.5 hour.

Day 2, 01:30 — Chinese customs documentation commences. Independent sequential review process. Risk assessment, manifest verification, commodity inspection clearance: approximately 15.0 hours average.

Day 2, 16:30 — Chinese documentation complete. Train waits for availability of Chinese standard-gauge ore wagons: average 7.5 hours.

Day 2, 24:00 — Chinese-gauge wagons coupled to consist. Train departs Erenhot for destination smelter.

Total elapsed time: approximately 40 hours (range across all crossings: 27 to 37 hours). Value-added time: 3.0 hours (bogie exchange only). Process Cycle Efficiency: 9.4 percent. Under the Phase 1 optimized scenario, expected total dwell time reduces to 5 to 6 hours, comprising 1.5 hours entry procedures, 3.0 hours bogie exchange, and 0.5 hours transfer.

Appendix C: Smelter Mass Balance

Annual mass balance for proposed Erdenet copper smelter, based on 2025 EMC production volumes:

- Concentrate feed: 574,000 tonnes per annum (dry basis), 22.5% Cu, 29% Fe, 31% S
- Contained copper in feed: 129,150 tonnes
- Silica flux addition: ~57,000 tonnes per annum (slag chemistry control)
- Oxygen addition: ~120,000 tonnes per annum (60–80% O₂ enrichment)
- Copper matte produced: ~198,000 tonnes at 65% Cu
- Slag produced: ~650,000 tonnes at 0.8% Cu (for slag cleaning)
- Blister copper from Peirce-Smith converters: ~126,000 tonnes at 98.5% Cu
- Anode copper from anode furnaces: ~125,000 tonnes at 99.5% Cu
- Copper cathode (LME Grade A): 124,100 tonnes at 99.99% Cu
- Sulfuric acid by-product: ~450,000 tonnes per annum
- Overall copper recovery (concentrate to cathode): 96.1%
- Mass reduction factor: 4.6 to 1 (574,000t concentrate → 124,100t cathode)
- Freight volume reduction: 78% (574,000t → 124,100t)
- Annual logistics cost saving at \$84/tonne rate: USD 36.2 million