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Beyond Hardness: A Total Cost of Ownership and Application-Environment Framework for Wear Resistant Steel Selection in Indonesian Mining

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Abstract

Background: Wear resistant (WR) steel selection in Indonesian mining is typically driven by nominal hardness and unit price, criteria that overlook the dominant MRO cost drivers: service life, change-out frequency, and downtime. No published framework integrates application-environment classification, multi-grade benchmarking, mill test certificate (MTC) verification, and parametric Total Cost of Ownership (TCO) analysis for this context.
Objective: This study develops a four-step evaluation framework connecting application environment, material technical parameters, quality verification, and lifecycle cost, applied to Indonesian coal and gold/copper-gold mining.
Methods: A mixed-methods applied engineering evaluation combined: structured consultation with three informants — an end-user metallurgy manager at a Central Sulawesi gold operation and two mineral processing equipment OEM engineers — cross-checked against maintenance-scheduling records and throughput data; benchmarking of seven WR steel grades against manufacturer datasheets (JFE EVERHARD, Hardox 400/450) and a representative MTC; and a parametric 34-component TCO model with three-scenario (conservative, base-case, optimistic) sensitivity testing, supported by eight peer-reviewed sources selected on defined inclusion criteria.
Results: Coal mining represents a continuous-abrasion environment requiring medium-to-high hardness with good weldability; gold and copper-gold mining represent high-impact, severe-abrasion environments requiring verified toughness alongside hardness. Across the representative component set evaluated and across all three sensitivity scenarios, downtime and installation cost reduction consistently outweighed material cost as the dominant driver of estimated annual savings. Notably, the upgrade pathway with the highest estimated saving (mild steel to NM400) involves a grade priced above the material it replaces, yet still generates the largest net saving through reduced shutdown frequency — indicating that unit price is not a reliable proxy for total ownership cost. These findings are outputs of a parametric simulation model and should be read as directional estimates pending field validation, not as field-measured results.
Conclusion: WR steel selection should be treated as an integrated technical and operational decision, not a price-per-kilogram procurement exercise. The four-step framework offers decision-makers a replicable, low-cost screening tool — environment classification, material benchmarking, MTC verification, TCO evaluation — that procurement and maintenance teams can apply before formal investment decisions, shifting the basis of selection from a unit-cost basis toward evidence-based lifecycle cost. Field validation of downtime rates and actual service life remains the priority next step.

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INTRODUCTION

The mining industry in Indonesia operates across two structurally distinct environments that create fundamentally different material demands (Libassi, 2023; Sangadji, 2021). Open-cut coal operations in Kalimantan and Sumatra process high volumes of relatively soft material under conditions of continuous abrasion (Jati et al., 2021). In contrast, hard-rock gold and copper-gold mines in Papua and Sumbawa subject equipment to repeated impact from dense ore, generating a combination of severe abrasion and mechanical shock that no single material specification can address uniformly (Lucas, 2018). The scale of these operations is not trivial: the International Energy Agency (2024) identifies Indonesia as one of the principal actors in the global thermal coal trade, while PT Freeport Indonesia (2025) reported 2024 output of approximately 1.8 billion pounds of copper and 1.86 million ounces of gold. At this production volume, even marginal improvements in the service life of wear components translate directly into measurable reductions in maintenance costs, downtime, and total production costs.

Studies in comparable mining contexts indicate that wear-related component failures account for 30–50% of total unplanned equipment downtime, with annual maintenance expenditures on wear parts ranging from 15–25% of total operational costs in abrasion-intensive operations (Al-Chalabi, 2022; Florea et al., 2025). In the Indonesian context, where processing facilities operate at high throughput under harsh abrasive conditions, the cumulative cost of premature wear component failure represents a significant and addressable source of operational losses.

Despite this economic relevance, material selection for mining wear components in Indonesia often remains anchored to two heuristics: nominal hardness and unit price per kilogram (Firmanto et al., 2025; Hasibuan et al., 2025; Maia, 2018). This approach is inadequate on both technical and economic grounds. Technically, the relationship between hardness and field wear performance is non-linear and strongly application-dependent—laboratory studies consistently show that wear mechanisms, contact geometry, abrasive characteristics, and microstructural behaviour collectively determine actual service life rather than hardness alone (Ratia et al., 2013; Zemlik et al., 2024). Economically, reducing the total cost of ownership (TCO) to purchase price systematically underweights the dominant cost drivers: downtime during change-outs, installation labour, and replacement frequency. As Al-Chalabi (2022) and Komonen (2002) demonstrate, acquisition cost is rarely the dominant variable in wear component lifecycle economics; operational costs are.

The research gap this study addresses is specific. Individual dimensions of the wear-resistant (WR) steel evaluation problem appear in isolation across the literature: material testing studies Zemlik (2024) and Saha (2020), liner and chute design analyses Grasser (2024); Chen (2017), component reliability studies Florea (2025), and equipment replacement cost models (Al-Chalabi, 2022; Castanón et al., 2024).

What is absent is a framework that connects all four dimensions—application environment classification, multi-grade technical benchmarking, mill test certificate (MTC) verification, and parametric TCO analysis—into a single, replicable evaluation sequence oriented toward practical implementation in the Indonesian mining context. Unlike prior TCO frameworks for mining equipment Al-Chalabi (2022) and Castanón (2024), which focus on replacement timing optimisation for major capital assets, this study integrates material grade benchmarking and quality certification verification into the cost evaluation process, a dimension absent from existing frameworks. Similarly, while material selection models in the literature address wear properties Zemlik (2024) and Saha (2020) none combine MTC-based quality verification with full-site parametric TCO modelling within the Indonesian mining context.

The novelty of this study is the integration itself, not any single constituent element. To the best of the author's knowledge, no published study has integrated environment-based screening, multi-grade technical benchmarking, MTC-based quality verification, and parametric TCO modelling into one sequential decision framework, demonstrated here against components drawn from a full-site portfolio in an Indonesian mining context. This positions the contribution as methodological and integrative rather than a discovery of new material behaviour.

This study develops and demonstrates that four-step framework. The contribution is methodological and integrative: the analytical sequence is designed to be reproduced by materials engineers, procurement managers, and mine planners using comparable technical documents and operational cost data from their own operations. Coal mining serves as the representative continuous-abrasion environment; gold and copper-gold mining serve as the representative high-impact, severe-abrasion environment. This distinction, grounded in the wear mechanism rather than the commodity, is the structural basis of the evaluation, as shown in Table 1.

Table 1. Application Environment Classification of WR Steel in Indonesian Mining Operations

Mining Environment	Dominant Wear Mechanism	Typical MRO Wear Parts	Required Material Characteristics	Operational Efficiency Relevance
Coal mining (Open-cut: Kalimantan, Sumatra)	High-volume continuous abrasion from coal, clay, sand, and slurry under high throughput volumes	Dump truck body liner, conveyor chute, hopper, bucket floor, feeder plate	Medium–high hardness (HBW 370–480); good weldability (CE ≤ 0.50); suitable thickness for repetitive replacement; verified Charpy toughness	Extended service life; reduced replacement frequency; lower scheduled maintenance intervention
Gold and copper-gold mining (Hard-rock: Papua, Sumbawa)	High impact combined with severe abrasion from hard rock and ore; risk of gouging, cracking, and deformation	Bucket liner, dump truck sidewall, slurry pipeline, crusher liner, feeder plate, cutting edges	Higher hardness (HBW 425–550); verified impact toughness (≥ 45 J at −40°C); resistance to gouging and cracking; full MTC with Charpy data	Reduced unplanned downtime; improved equipment availability; lower change-out frequency; lower total lifecycle cost

Note: MRO = Maintenance, Repair, and Operations; CE = Carbon Equivalent; HBW = Brinell Hardness; MTC = Mill Test Certificate. Sources: JFE Steel (2025), Saha (2020), Xuewei (2025), author classification.

Table 1 makes the core analytical logic explicit: the starting point for material selection is environment mapping, not a grade comparison table. A material appropriate for a coal chute with stable abrasion resistance, good weldability, and moderate hardness will systematically underperform in a hard-rock crusher feed zone, where the same hardness without verified toughness creates a risk of cracking rather than improved wear resistance. This study builds from this classification through three subsequent analytical stages.

The aim of this study is to develop and validate a four-step integrated evaluation framework for wear-resistant steel selection applicable to Indonesian coal and gold/copper-gold mining operations. The primary benefit for practitioners is a replicable decision sequence that replaces intuitive or price-driven material selection with an evidence-based analytical process connecting wear environment, material properties, quality verification, and lifecycle cost. For the academic community, this study contributes a quantified, site-grounded application of TCO principles to the wear-resistant materials domain. The expected implication is a measurable reduction in unplanned downtime and total MRO costs for operations adopting the framework, with the Central Sulawesi case study providing an empirical foundation for future field-validation research.

METHOD

This study employed a mixed-methods applied engineering evaluation approach, integrating expert consultation for the derivation of primary TCO assumptions with secondary-data technical benchmarking, an approach appropriate for materials and engineering management research when direct field testing is beyond the study's scope (Castanón et al., 2024; Grasser et al., 2024).

The approach integrated four analytical stages corresponding to the four steps of the evaluation framework: application environment classification, technical material benchmarking, MTC-based quality verification analysis, and parametric TCO modelling with sensitivity testing. Figure 1 presents the framework structure and the logical flow between the stages.

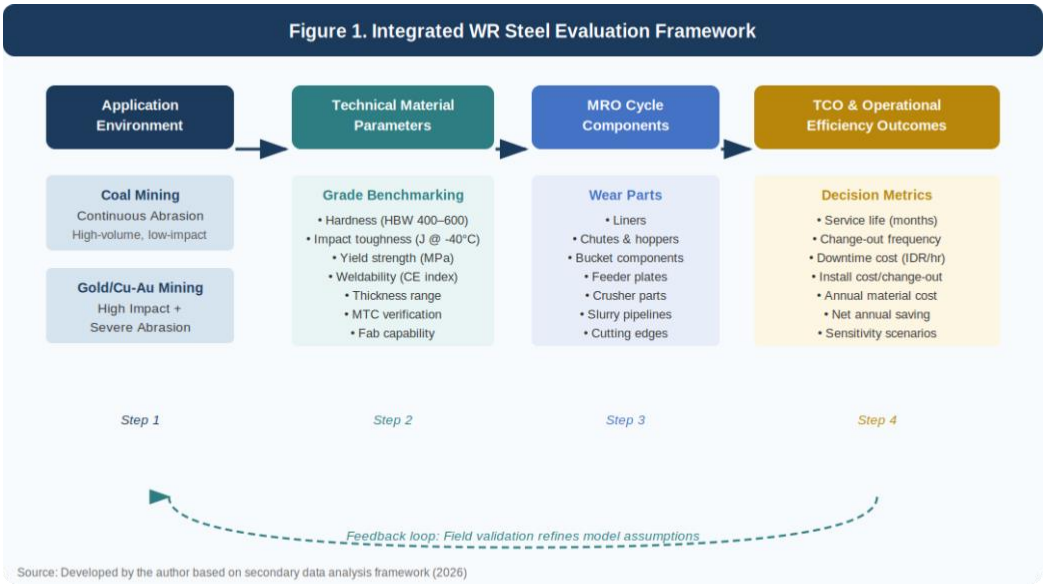

Figure 1. Integrated WR Steel Evaluation Framework (Four-Step Analytical Sequence)
Source: Developed by the author based on secondary data analysis (2026).

Data Sources and Inclusion Criteria

Two categories of data sources were used. The first category comprised technical and industrial documents: the JFE EVERHARD catalogue (2025) as a reference for Japanese abrasion-resistant steel grade classification, hardness ranges, chemical composition, toughness, and application scope; the Hardox 400 and Hardox 450 data sheets as internationally recognized benchmarks for hardness, yield strength, impact toughness, thickness range, weldability, and bendability; a representative mill test certificate sample for quality verification parameter analysis; and a parametric TCO model constructed by the author using a gold mining component portfolio as the illustrative context.

The second category comprised eight peer-reviewed journal articles identified through the following inclusion criteria: (1) published between 2013 and 2025 in indexed journals; (2) primarily focused on one or more of the following topics: abrasive wear of steels, impact-abrasive wear, mining material handling systems, mining component reliability and maintainability, or mining equipment replacement economics; (3) involved methodologies including experimental testing, simulation, or quantitative cost modelling; and (4) were relevant to at least one of the two application environments defined in this study. Articles addressing purely metallurgical alloy development without application context, or those restricted to non-mining industrial wear without transferable findings, were excluded.

Technical Benchmarking Protocol

Material comparisons were conducted across six parameters: (1) Brinell hardness range (HBW); (2) typical yield strength (MPa); (3) Charpy impact toughness at −40°C, where available; (4) available thickness range; (5) weldability expressed through the carbon equivalent index or manufacturer guidance; and (6) quality certification evidence. This parameter set covered the primary determinants of field performance identified in the peer-reviewed literature Ratia (2013), Zemlik (2024), Saha (2020), as well as the fabrication constraints most relevant to

Indonesian mining workshop practices.

TCO Model and Sensitivity Analysis

The TCO model evaluated the following variables for each wear component: current and alternative grades, component weight and quantity, unit price per kilogram, estimated service life in months, annual change-out frequency, annual material cost, downtime rate in IDR per hour, hours of downtime per change-out, installation cost per change-out, and estimated annual savings. The mathematical structure of the model was as follows. For each component *i*, the annual material cost was calculated as follows:

$$\text{Annual Material Cost}_i = (\text{Component Weight [kg]} \times \text{Unit Price [IDR/kg]} \times \text{Annual Change-out Frequency})$$

The annual change-out frequency was derived as follows:

$$\text{Frequency}_i = 12 / \text{Service Life [months]}$$

Annual downtime savings were calculated as follows:

$$\text{Downtime Savings}_i = (\text{Frequency\_current} - \text{Frequency\_alternative}) \times \text{Hours per Change-out} \times \text{Downtime Rate [IDR/hr]}$$

Annual installation savings followed the same frequency differential multiplied by the installation cost per change-out. The total annual savings per component were calculated as:

$$\text{Total Annual Savings per Component} = \text{Material Cost Differential} + \text{Downtime Savings} + \text{Installation Savings}$$

The portfolio total was calculated as:

$$\text{Portfolio Total} = \Sigma(\text{Savings}_i) \text{ across all } n \text{ components}$$

The model was explicitly designed as a parametric evaluation instrument rather than a financial forecast. To address the inherent limitations of secondary-data cost assumptions, three scenarios were defined: 1) Conservative scenario: Service life improvement was assumed to be 50% of the base case, with downtime benefit realization set at 40%. This scenario represented a skeptical interpretation consistent with partial field validation. 2) Base-case scenario: Service life improvement and downtime reduction figures were based on supplier data and comparable published field studies. 3) Optimistic scenario: Service life improvement was assumed to be 150% of the base case, with downtime benefit realization set at 100%. This scenario represented the full realization of theoretical material performance advantages.

The sensitivity analysis output illustrated the range of plausible outcomes and identified downtime rate assumptions as the dominant variable requiring field validation before any investment decision was formalized.

Expert Consultation for TCO Assumption Derivation

The two primary quantitative assumptions underpinning the TCO model — downtime rate and hours of downtime per change-out — were derived through structured consultation with three independent external informants, corroborated against the author's organisation's internal field-sales dataset. Informant A is the metallurgy/maintenance manager holding full-site budgetary and scheduling authority over wear plate maintenance (34 evaluated components) at a gold mining operation in Central Sulawesi, Indonesia. Informants B and C are engineering representatives from two separate global mineral processing equipment OEMs, each independently involved in the installation, commissioning, or maintenance advisory scope for wear-critical components at comparable operations. These three parties represent distinct organisations with no reporting relationship to one another and, in the case of the two OEMs, no direct commercial interest in the wear-plate cost outcome of this study.

The downtime rate (IDR 1,200,000,000 per hour; approximately USD 66,000 per hour at the FX rate prevailing at the time of consultation) was derived from Informant A's site-level throughput and commodity-value data and was corroborated by Informants B and C against their own cross-site experience of comparable processing-facility downtime costs. The hours of downtime per change-out (12 hours, encompassing preparation, removal, installation, testing, and post-installation inspection) were supplied by Informants B and C based on documented OEM maintenance-scheduling parameters for the component types evaluated, and were consistent with Informant A's site-level scheduling records.

This multi-informant structure — end-user operational authority (Informant A) cross-checked against independent OEM technical experience (Informants B, C) — provides corroboration across organisational boundaries rather than internal consistency-checking within a single informant's own records. It is nonetheless a limited and non-random sample of three informants rather than a systematic multi-site survey, and this scope is treated as a limitation in Section 4. Individual informant and organisational identities are withheld at their request (Anonymised Informants A, B, C, personal communication, 2026).

This expert consultation component elevates the methodological basis of the study from purely secondary data to a mixed-methods applied engineering evaluation, in which primary operational parameters anchor the TCO model and secondary data (datasheets, peer-reviewed literature) provide the technical benchmarking and theoretical grounding. The breadth of the site scope — 34 components spanning the full processing circuit from ROM hopper to tailings handling — strengthens the generalisability of the findings beyond any single component type. The three-scenario sensitivity analysis (Section 2.3) was designed to acknowledge that expert-derived assumptions carry inherent uncertainty, and to demonstrate that the central structural finding — that downtime dominance over material price is so complete as to render price-per-kilogram comparisons analytically irrelevant in the dominant upgrade pathway — holds robustly across the full plausible range of assumptions, not only at base case.

Separately, the author's organisation's internal field-sales and technical dataset — accumulated over approximately four years of commercial engagement in wear-resistant steel supply — was used to benchmark commercial pricing and MTC-quality parameters feeding the model. This dataset is not treated as an independent informant; it is the author's own commercial data and is disclosed as such in the conflict-of-interest statement.

Validity and Ethical Considerations

Analytical validity was maintained through document triangulation: manufacturer technical data, MTC evidence, academic literature, expert-derived operational parameters, and TCO model outputs were cross-referenced rather than treated as independent claims. Where sources were incomplete or conflicting, a conservative interpretation was applied. The expert consultation involved one primary informant with corroborating multi-source verification; no sensitive personal data were collected. The author disclosed the commercial affiliation in the conflict of interest statement at the beginning of this paper, and the informant's anonymity was preserved in accordance with the stated preference.

RESULTS AND DISCUSSION

Results

Application Environment Classification

The analysis confirms that WR steel application conditions in Indonesian mining operations are not homogeneous and cannot be adequately characterised by a single wear parameter. This is not merely a theoretical observation, it has direct practical consequences. A material specified for continuous sliding abrasion will fail prematurely under high-impact loading, not because it is of low quality, but because it was never designed for that specific loading condition.

Coal mining presents a continuous-abrasion environment. Material handling involves high volumes of relatively soft materials (such as coal, clay, sand, and slurry) processed at high throughput rates. The dominant wear mechanism is repeated contact under sliding conditions, consistent with Xuewei (2025), who demonstrated through discrete element method (DEM) simulations that coal drainage chutes in open-pit operations generate primarily sliding-abrasion mechanisms. The material requirements in this environment are stable abrasion resistance, good weldability for field repair, and sufficient plate thickness to accommodate repetitive wear without premature failure of the base material.

Gold and copper-gold mining present fundamentally different operating conditions. Hard-rock ore and waste rock generate high-energy impact events at loading points, combined with severe abrasion as materials pass through chutes, hoppers, and bucket components. Saha (2020) demonstrated experimentally that steels operating under impact-abrasive conditions require a materially different hardness–toughness balance compared with abrasion-only applications, and that optimising hardness alone at the expense of toughness increases the risk of cracking under impact rather than gradual material loss. For crusher feed zones and bucket lips in hard-rock operations, a material with verified Charpy impact toughness is not a premium specification; it is a baseline safety requirement.

This two-environment classification serves as the screening filter for all subsequent analytical stages. The suitability matrix presented in Figure 3 operationalises this logic across the full grade-by-application space, making the classification actionable at the procurement level.

Technical Material Benchmarking

The consolidated benchmarking of seven material grades is presented in Table 2. Three findings emerge that are directly relevant to material selection decisions in Indonesian mining practice.

Table 2. Technical Benchmarking of Wear Resistant Steel Grades

Material / Grade	Hardness Range (HBW)	Yield Strength (MPa, typical)	Charpy Toughness (J @ −40°C)	Thickness Range (mm)	Weldability (CE)	Application Notes
JFE EVERHARD C400	370–430	≥ 1,000	≥ 27 (Standard Series)	3.2–100	≤ 0.50	Standard series; primary focus on hardness. Suitable for liners, chutes, hoppers, and bucket floors under continuous abrasion. JFE guarantees chemical composition, HBW, and toughness per catalogue.
JFE EVERHARD C450	425–475	≥ 1,150	≥ 27	3.2–80	≤ 0.53	Higher hardness; better resistance to denting. Suitable for more intensive abrasion. Fabrication note: verify preheat requirement at thickness ≥ 25 mm.
JFE EVERHARD C500 / C500LE	470–530	≥ 1,300	C500LE: ≥ 27 @ −40°C	3.2–65	≤ 0.58	High-abrasion and impact zones. LE series provides verified low-temperature toughness. Appropriate for

						hard-rock crusher liners and bucket lips. Controlled preheat and specified welding procedures are mandatory.
Hardox 400 (SSAB)	370–430	~1,100	45 J @ −40°C	0.8–160	CE ~0.43	Industry-standard benchmark for continuous abrasion. Best-in-class toughness-to-hardness ratio at 400 HBW. Excellent weldability; widest available thickness range. Preferred benchmark for coal mining MRO components.
Hardox 450 (SSAB)	425–475	~1,250	50 J @ −40°C	0.8–100	CE ~0.50	50 HBW gain over 400 provides measurable improvement in denting and abrasion resistance. Recommended for hard-rock bucket liners and sidewalls where impact combines with abrasion. Documented toughness is a key differentiator.
NM400 / NM450 (Asian market, with MTC)	370–430 / 425–475	Varies — verify per MTC	Varies — must confirm ≥ 27 J per MTC	Typically 3.2–80	Verify — some mills show higher C content	Commercially viable alternative for cost-sensitive applications. Acceptable only with full MTC verification. Toughness consistency varies by mill, standard, and heat; batch-level verification is mandatory. Not suitable for critical impact-abrasion zones without documented Charpy data.
NM500	470–530	Varies —	Varies —	Typically	Verify —	Highest hardness in

(Asian market, with MTC)	verify per MTC	higher brittleness risk	3.2–50	preheat mandatory	Asian alternative range. Service life benefit over NM400/NM450 may be marginal (6–10%) in several components. Full MTC with Charpy data is non-negotiable for impact-abrasion applications. TCO benefit depends heavily on unit price differential (see Section 3.4).

Note: CE = Carbon Equivalent (Pcm or IIW depending on source). Hardness and toughness values from (JFE Steel, 2025). NM grade properties are indicative ranges based on available market data; actual values must be confirmed per MTC for each procurement batch. A visual radar chart comparing all seven grades across the six benchmarking parameters (hardness, toughness, yield strength, thickness range, weldability CE, and MTC reliability) is recommended as a supplementary figure to facilitate multi-parameter trade-off assessment in practitioner contexts.

The first finding is that toughness, not hardness, is the differentiating parameter in hard-rock impact–abrasive applications. The Hardox grades carry publicly documented Charpy impact values (45 J and 50 J, respectively, at −40°C); most NM-grade MTCs from Asian suppliers do not consistently include Charpy data unless explicitly requested at the time of order placement. For impact-critical applications, such as crusher liners, bucket lips, and slurry pipeline bends, this gap is not merely a documentation issue; it represents a material fitness-for-purpose risk. Zemlik (2024) confirm this finding from a different perspective: their comparative study of Hardox steel and Hadfield cast steel shows that damage mechanisms such as micro-ploughing and fragment breakout are governed by microstructural characteristics beyond bulk hardness.

The second finding is that weldability has a direct cost implication that is almost never captured in material price comparisons. Materials with higher carbon equivalent values require preheating, slower welding travel speeds, and more skilled operators, all of which increase installation time and, consequently, downtime costs during change-outs. The NM500 grade, with its higher carbon equivalent and mandatory preheating requirement, may appear cheaper on paper but carries a hidden installation cost penalty that can partially or fully offset its price advantage, depending on the workshop capabilities available at the mine site.

The third finding is that the suitability of any grade is application-specific and cannot be determined based on a single material property. Figure 2 presents the consolidated suitability assessment across grade–application combinations, translating the benchmarking data into a practical screening tool.

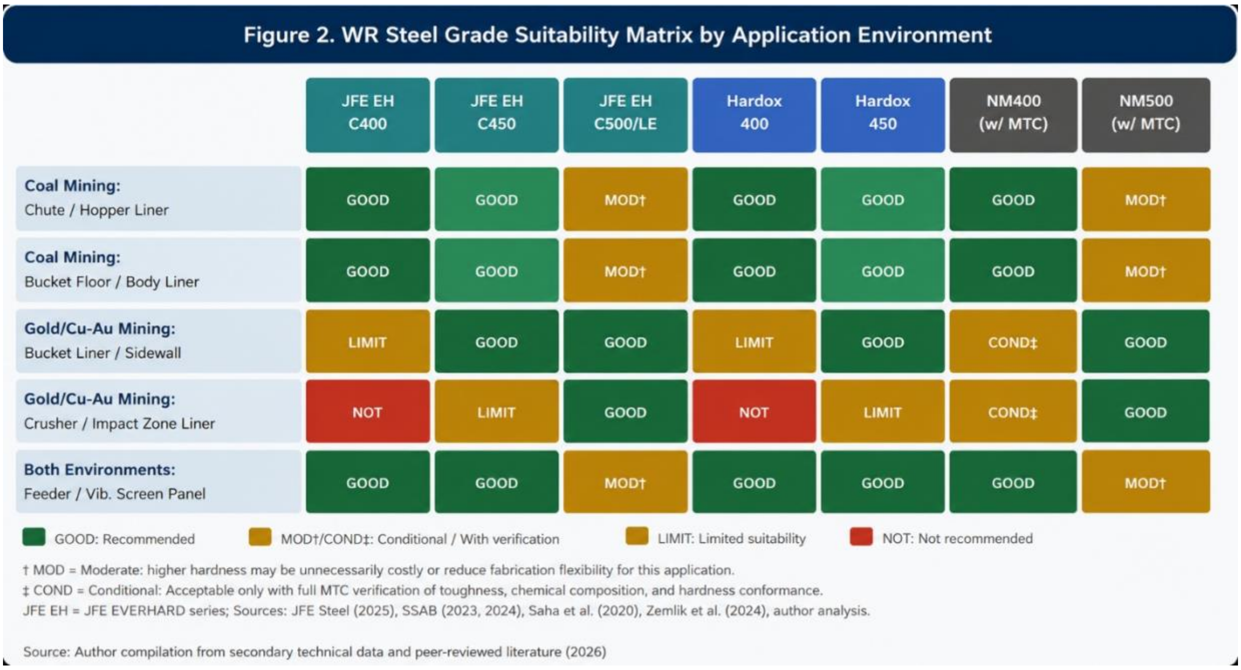

Figure 2. WR Steel Grade Suitability Matrix by Application Environment

	JFE EH C400	JFE EH C450	JFE EH C500/LE	Hardox 400	Hardox 450	NM400 (w/ MTC)	NM500 (w/ MTC)
Coal Mining: Chute / Hopper Liner	GOOD	GOOD	MOD†	GOOD	GOOD	GOOD	MOD†
Coal Mining: Bucket Floor / Body Liner	GOOD	GOOD	MOD†	GOOD	GOOD	GOOD	MOD†
Gold/Cu-Au Mining: Bucket Liner / Sidewall	LIMIT	GOOD	GOOD	LIMIT	GOOD	COND‡	GOOD
Gold/Cu-Au Mining: Crusher / Impact Zone Liner	NOT	LIMIT	GOOD	NOT	LIMIT	COND‡	GOOD
Both Environments: Feeder / Vib. Screen Panel	GOOD	GOOD	MOD†	GOOD	GOOD	GOOD	MOD†

GOOD: Recommended MOD†/COND‡: Conditional / With verification LIMIT: Limited suitability NOT: Not recommended

† MOD = Moderate: higher hardness may be unnecessarily costly or reduce fabrication flexibility for this application.
‡ COND = Conditional: Acceptable only with full MTC verification of toughness, chemical composition, and hardness conformance.
JFE EH = JFE EVERHARD series; Sources: JFE Steel (2025), SSAB (2023, 2024), Saha et al. (2020), Zemlik et al. (2024), author analysis.

Source: Author compilation from secondary technical data and peer-reviewed literature (2026)

Figure 2. WR Steel Grade Suitability Matrix by Application Environment
Source: Author compilation from JFE Steel (2025), Saha (2020), Zemlik(2024). GOOD = recommended; MOD/COND = moderate or conditional (see figure notes); LIMIT = limited suitability; NOT = not recommended.

MTC-Based Quality Verification

The MTC is not an administrative formality. It is the primary document through which an alternative material from the Asian market can be technically assessed at the heat and plate levels before installation. In a market where product naming conventions for NM-series steels are not standardised across mills, and where proprietary production standards (such as Q/BHNM-series specifications) may differ from assumed Cr-Mo-Ni alloy compositions, relying solely on grade names and hardness values introduces a material fitness risk that the MTC directly mitigates. Table 3 details the key MTC parameters and their engineering relevance.

Table 3. MTC Parameters and Their Engineering Significance in Mining Applications

MTC Parameter	What It Certifies	Engineering Significance	Risk If Not Verified
Material standard & grade	Confirms the specification the material was produced to	Ensures grade suitability for the target application environment	Grade mismatch: coal-duty material deployed in hard-rock impact zone
Chemical composition (C, Si, Mn, Cr, Mo, B, Ti)	Heat-level elemental content; basis for CE calculation	Determines hardenability, toughness, weldability; enables CE index calculation for preheat decision	Undetected high-CE: cracking during welding; hydrogen-induced cracking in heat-affected zone
Tensile test (Rp0.2, Rm, A%)	Yield strength, tensile strength, elongation at fracture	Structural integrity under impact loading; ductility before fracture	Insufficient yield: permanent deformation under impact; inadequate elongation: brittle fracture without warning
Charpy impact test (J at	Energy absorbed at notch — the primary	Critical differentiator for high-impact	Undisclosed low toughness in NM grades:

specified temperature)	toughness indicator	environments; separates toughness-optimised grades from hardness-only grades	catastrophic cracking in bucket lips or crusher liners under hard-rock impact loading
Brinell hardness (HBW)	Surface hardness at multiple measurement points	Directly related to abrasion resistance; value must fall within the specified range, not merely above a minimum	Hardness out of specification: premature wear at the lower end or reduced fabricability at the upper end
Ultrasonic test (UT)	Internal defect detection: laminations, inclusions, segregation zones	Prevents deployment of plates with internal defects that could cause in-service fracture under cyclic loading	Undetected lamination: sudden plate fracture during operation; safety hazard and unplanned downtime
Dimensional and visual inspection	Plate dimensions, flatness, surface condition	Fabrication fit-up accuracy; surface defects as wear initiation sites	Dimensional non-conformance: rework cost and installation delay; surface defects: premature localised wear

Note: HAZ = Heat-Affected Zone; CE = Carbon Equivalent; Charpy test temperature should be specified at procurement stage to match application environment requirements. Sources: JFE Steel (2025), Zemlik (2024), author analysis.

The practical implication of Table 3 is that material procurement for mining MRO applications should function as a technical verification process rather than as a commodity purchase. For Hardox and JFE EVERHARD grades, the MTC consistently provides all parameters listed above because they are embedded in the product standards. For NM-series alternatives, the MTC content and reliability vary by mill, production standard, and batch. Charpy toughness data, in particular, are frequently absent or reported at a non-standard temperature unless explicitly specified in the purchase order.

This finding reinforces the observations of Grasser (2024) and Chen (2017) from the liner design and material-handling perspectives: liner failure in mining chutes and bins frequently originates from material property variability rather than from inherent grade unsuitability. The MTC requirement is therefore not merely a bureaucratic safeguard; it is the mechanism through which specification risk is managed in a commercially heterogeneous supply environment.

TCO-Based Operational Efficiency Evaluation

The central argument of this study — that operational cost, not material price, determines the economics of WR steel selection — is tested here against a representative subset of the full-site 34-component TCO evaluation conducted at a gold mining operation in Central Sulawesi, Indonesia, representing a site-wide annual wear plate consumption of 60–80 metric tonnes. Table 4 presents seven components, selected to represent the two dominant upgrade pathways identified across the full site evaluation (mild steel to NM400, and Hardox 450 to NM500); the underlying component list, wear lives, quantities, and unit prices are drawn from the actual site scope as documented through the expert consultation (Anonymised Informant A, 2026). This subset is presented in full detail here because the complete 34-component dataset is not reproducible within the length constraints of this article; the seven components shown are illustrative of the pattern observed across the full portfolio, not a substitute for it, and the totals below should be read strictly as the sum of these seven components, not as a site-wide figure.

Table 4. TCO Evaluation: Component-Level Results, Gold Mining Base-Case Scenario

Compone	Curre	Alternati	Curre	Est.	Material	Downtim	Dominant Efficiency

nt	nt Grade	ve Grade	nt Life (mo.)	Life (mo.)	Cost Saving (IDR M, indicative)	e + Install Saving (IDR M, indicative)	Driver
ROM Hopper / Crusher Feed Hopper	Mild Steel	NM400	3.0	4.5	45	135	Downtime reduction (75% of saving)
CIL Feed Box Liners	Mild Steel	NM400	4.0	6.0	40	170	Downtime reduction (81% of saving)
Conveyor Chutes: ROM–Crusher	Mild Steel	NM400	4.0	6.0	35	155	Downtime + frequency reduction (82% of saving)
Jaw Crusher Discharge Chute	Hardox 450	NM500	5.0	5.2	55	40	Material unit price (58%) — low life gain; validate before proceeding
Ball Mill Feed Chute Liners	Hardox 450	NM500	6.0	6.3	50	60	Mixed — marginal life gain; MTC toughness validation required
Vibrating Screen Deck Panels	Mild Steel	NM400	2.0	3.0	30	240	Downtime reduction — high component count amplifies impact (89% of saving)
Ball Mill Shell Liners	Hardox 450	NM500	8.0	8.4	60	100	Combined — large component count; sensitivity analysis warranted
TOTAL (Base Case)					**315**	**900**	**Downtime + installation cost reduction dominant in this subset: ~74% of the IDR 1,215 million combined saving (IDR 900M downtime+install vs IDR 315M material). Full-portfolio totals require the complete 34-component dataset (see Section 4, Limitations).**

Note: Values for the seven components shown are drawn from the full-site evaluation of a gold mining operation in Sulawesi, Indonesia (Anonymised Informant A, 2026; see Section 2.4). Site-wide wear plate scope: 60–80 metric tonnes/yr across 34 components; the seven components above are a representative subset, not the full portfolio. Downtime rate: IDR 1,200,000,000/hour (≈USD 66,000/hr at IDR 18,080/USD), derived from production throughput loss × commodity price. Hours per change-out: 12 hours from maintenance scheduling records. Installation cost: IDR 9,040,000/change-out. Within this subset, the Mild Steel → NM400 pathway (4 of 7 components shown) illustrates that NM400 costs 76.5% more per kilogram than mild steel, yet still produces a net positive saving once downtime and installation cost are included — the material cost increase is more than offset by fewer shutdowns. The Hardox 450 → NM500 pathway (3 of 7 components shown) illustrates the opposite mechanism: NM500 costs 27% less per kilogram, but the life gain is only 4.0–6.7%, so the saving case rests more heavily on the price differential than on shutdown avoidance. The complete 34-component dataset is beyond the scope of this article; the seven components shown are presented as a representative illustration of the two upgrade pathways identified across the full site evaluation. Sources: Anonymised Informants A, B, C (2026); Al-Chalabi et al. (2022); Florea et al. (2025); SSAB (2023, 2024); JFE Steel (2025).

The most striking pattern in Table 4 is not simply that downtime savings dominate — it is the mechanism involved. Within this seven-component subset, downtime and installation cost reduction (IDR 900 million) accounts for roughly three-quarters of the combined IDR 1,215 million saving shown, with material price differences contributing the remaining share. This pattern is most stark in the mild steel-to-NM400 pathway: NM400 costs 76.5% more per kilogram than mild steel, which means material costs actually increase with the upgrade, yet the four components on this pathway in Table 4 still show a net positive saving once downtime and installation cost are included — generated substantially through fewer shutdowns, not through cheaper material. This is a pattern that a unit-price procurement framework is structurally incapable of identifying. These figures are outputs of a parametric simulation built on expert-derived assumptions (Section 2.4); they illustrate a directional mechanism observed across the site evaluation and should not be read as a validated, field-measured total, nor generalised to the mining industry beyond this site without further validation.

The Hardox 450-to-NM500 upgrade pathway shown in Table 4 tells a fundamentally different story. Here NM500 is 27% cheaper per kilogram than Hardox 450, but the life gain is only 4.0–6.7% depending on component type. The economic case for this pathway rests primarily on the unit price differential rather than on shutdown frequency reduction, making it more sensitive to the accuracy of the wear life assumptions than the mild-steel-to-NM400 pathway. For the jaw crusher discharge chute (4.0% life gain) and ball mill feed chute liners (5.0% life gain) shown in the table, the marginal life improvement warrants field validation before upgrade decisions are confirmed. This two-pathway distinction — one where material costs more but the saving case rests on shutdown avoidance, another where material costs less but contributes marginally to life extension — is precisely the type of nuance that an acquisition-price procurement approach is structurally incapable of surfacing. Extrapolating the component-level figures in Table 4 to a full-site total requires care: where multiple components are replaced within a single shared shutdown window, the downtime cost attaches to the shutdown event, not to each component independently, and must not be multiplied by component count without adjusting for this overlap — a modelling caveat that any full-portfolio extension of this framework must address explicitly. The dominance of downtime over material price also has boundary conditions: at sites with lower utilisation rates, longer standby buffers, or component replacement scheduled during planned maintenance windows rather than unplanned stoppages, the opportunity cost of downtime falls substantially, and the economic case for the mild-steel-to-NM400 pathway in particular would need to be re-evaluated against site-specific downtime rates rather than assumed to hold universally.

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Discussion

This finding is consistent with Al-Chalabi (2022), who demonstrated through a total cost of ownership minimisation model that acquisition cost is rarely the dominant variable in mining equipment lifecycle economics. The present study illustrates that principle with component-level detail not previously demonstrated in the published literature for this application context: within the representative subset evaluated, acquisition cost underperforms operational cost by a wide margin in the dominant upgrade pathway. . Florea (2025) support this mechanism by showing that abrasive wear directly drives replacement frequency, while replacement frequency acts as the multiplier through which downtime costs accumulate and ultimately exceed material price considerations. What this study adds, beyond confirming the direction of the relationship, is a worked, component-level illustration of the magnitude involved. To be precise about scope: the site's full wear plate portfolio comprises 34 components, but only seven were selected and presented in individual, component-level detail in Table 4; the remaining 27 were not separately analysed or reported in this article. Figure 3 visualises the savings composition; Figure 4 presents the full scenario range.

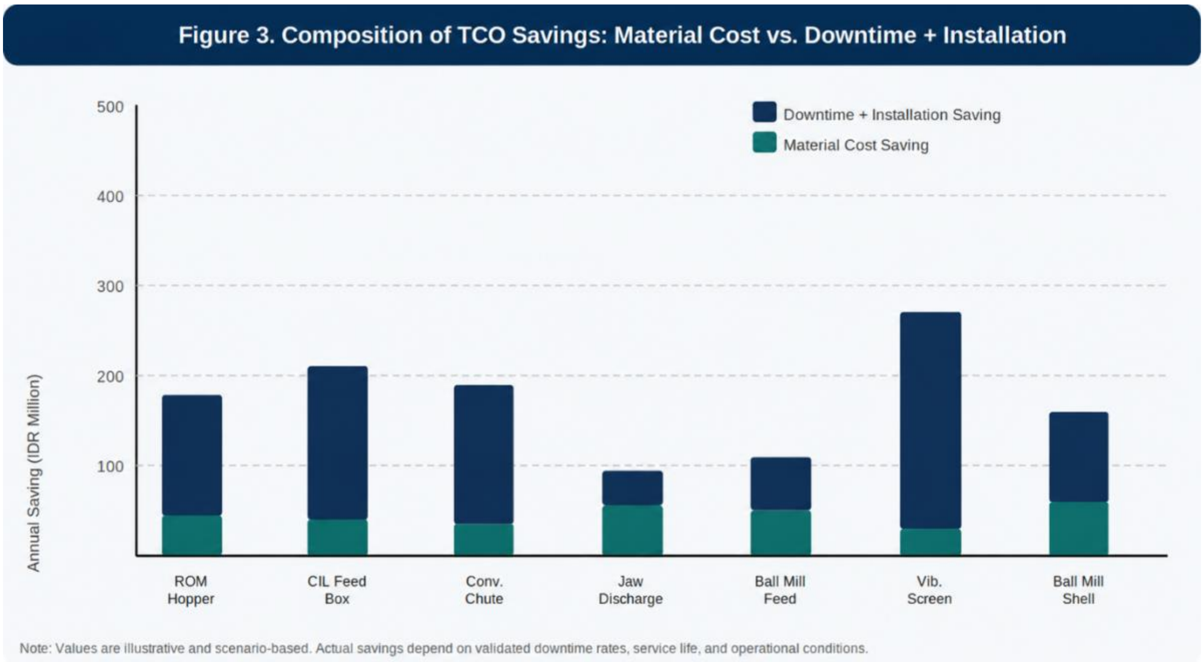

Figure 3. TCO Savings Composition: Material Cost vs. Downtime + Installation Cost Reduction (Base-Case Scenario)

Note: Each component group shows indicative base-case savings. The consistent dominance of the downtime + installation bar over the material cost bar is the central empirical finding of the TCO analysis. Actual values require field validation.

The sensitivity analysis (Figure 4) provides the epistemic framework for interpreting the scale of the TCO findings. The relative dominance of downtime over material cost within the subset evaluated rests on two primary assumptions: the downtime rate (IDR 1.2B/hr) and the service life improvement ratios. Both were derived from the multi-informant consultation described in Section 2.4, corroborated across an end-user operator and two independent equipment OEMs rather than resting on a single source. The conservative scenario reduces service life realisation to 50% and downtime benefit capture to 40%; the optimistic scenario applies 150% life gain and full downtime realisation. Across all three scenarios, the structural finding holds directionally: downtime reduction generates substantially more value than material price differences, though the absolute magnitude of that gap is sensitive to the downtime-rate assumption and has not been field-validated. The Hardox 450 → NM500 pathway is more scenario-sensitive and should be validated independently before site-level upgrade decisions are confirmed.

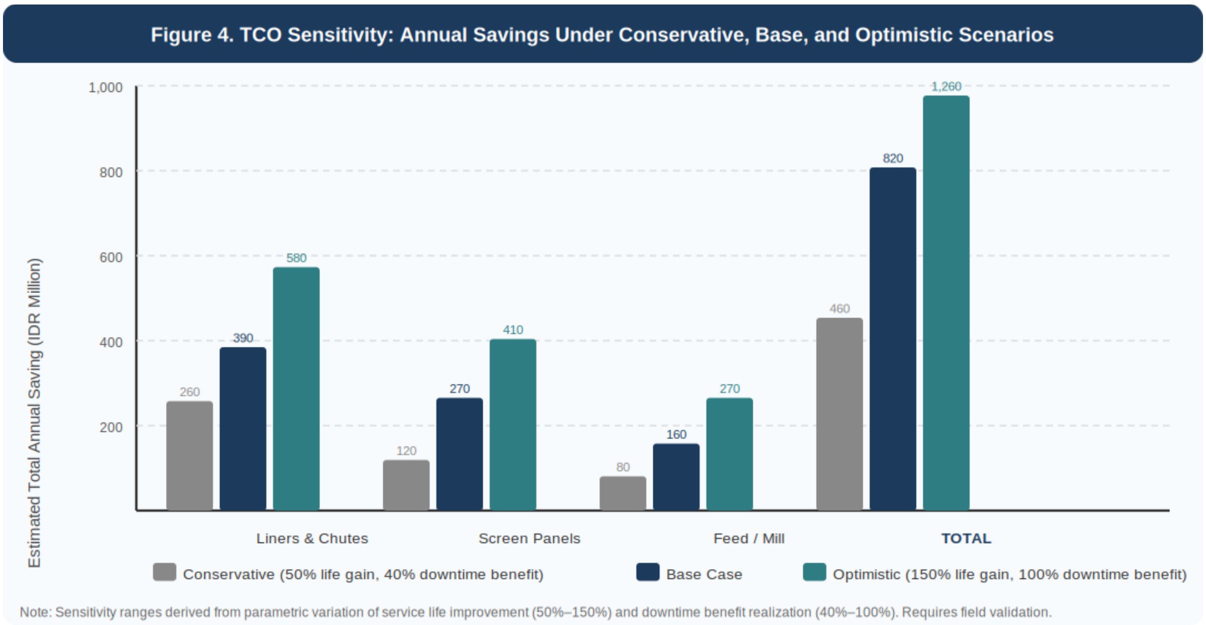

Figure 4. TCO Sensitivity Analysis: Estimated Annual Savings Under Conservative, Base-Case, and Optimistic Scenarios

Note: Conservative = 50% life gain realisation, 40% downtime benefit. Optimistic = 150% life gain, 100% downtime benefit. The dominant sensitivity driver is the downtime rate assumption; service life assumptions have secondary influence. All values are parametric estimates requiring field validation before formal investment decisions.

Comparison with Supporting Literature

Table 5 consolidates the relationship between this study's findings and the eight supporting journal articles, structured to show how each reference grounds a specific element of the four-step framework.

Table 5. Comparison of Study Findings with Supporting Literature

Reference	Research Domain	Key Transferable Finding	Framework Element Supported
(Zemlik et al., 2024)	Abrasive wear: Hardox vs. Hadfield cast steel	Wear is governed by microstructure and damage mechanisms, not hardness alone	Step 2 (Benchmarking): Hardness is necessary but insufficient; microstructural toughness properties must be evaluated alongside HBW.
(Saha et al., 2020)	Impact-abrasive wear of low-carbon steels	Impact-abrasive conditions require a hardness–toughness balance that pure hardness optimisation cannot achieve	Step 1 (Classification): Validates gold/Cu-Au environment as requiring a different material profile than continuous-abrasion coal environment.
(Grasser et al., 2024)	Wear liner design with inserts in mining chutes	Wear in chutes is driven by particle flow, impact geometry, and liner design — not material grade alone	Steps 1 & 2: Confirms chutes and liners as critical MRO wear points where environment geometry matters alongside material specification.
(Chen et al., 2017)	Abrasion wear of	Lining wear must be	Step 3 (MTC): Supports

	bin/chute linings in iron ore mining	resolved before material handling efficiency can improve	material verification as prerequisite for performance assurance in high-wear bins and chutes.
(Xuewei et al., 2025)	Wear in coal drain chutes, open-pit mining	DEM simulation confirms sliding-abrasion dominance in coal conveying systems	Step 1 (Classification): Directly supports continuous-abrasion classification for coal mining environments.
(Florea et al., 2025)	Abrasive wear, reliability, maintainability of quarry equipment	Abrasive wear drives replacement frequency and downtime — the dominant TCO variables	Step 4 (TCO): Grounds the link between wear rate, change-out frequency, and downtime cost as the dominant saving source.
(Castanón et al., 2024)	Mining equipment replacement time analysis	Replacement timing is optimised through availability, productivity, and downtime indicators	Step 4 (TCO): Supports use of operational performance indicators — not only material cost — in component replacement decisions.
(Al-Chalabi, 2022)	Total ownership cost model for mining equipment	Acquisition cost is rarely dominant in mining equipment lifecycle economics — operational cost is	Step 4 (TCO): Provides the theoretical grounding for TCO as the correct evaluation criterion, directly supporting the study's central argument.

Source: Author compilation from cited articles.

The literature comparison confirms that each step of the framework is anchored in established findings from distinct research streams. The primary contribution of this study is not any individual finding within those streams but rather their integration into a sequential, applied evaluation logic. What Zemlik (2024) and Saha (2020) established at the material level, Grasser (2024), Chen (2017), and Xuewei (2025) extended to the component and system levels, and what Florea (2025) and Al-Chalabi (2022) quantified at the cost level, this study assembles into a single practitioner-oriented decision sequence. From a broader engineering decision-support perspective, the four-step framework contributes a generalizable template for structured material selection in any procurement-intensive industrial context where TCO analysis has not yet displaced unit-price logic, making it transferable beyond the wear-resistant steel domain.

CONCLUSION

The central finding of this study is that wear resistant steel selection in Indonesian mining cannot be conducted rationally using hardness and price alone: application environment determines material requirement, material requirement determines grade, and grade — combined with verified properties and service life — determines operational cost outcome, a chain that a price-per-kilogram decision breaks at the first link. Two structural conclusions follow. First, application environment classification is the governing criterion: coal mining's continuous-abrasion environment and gold/copper-gold mining's high-impact environment require structurally different material profiles. Second, hardness is necessary but not sufficient — verified toughness, weldability, and MTC-documented quality conformance are equally essential, and in hard-rock applications Charpy toughness verification is arguably the single most commercially significant parameter, since its absence shifts the failure mode from gradual wear to sudden cracking. The theoretical contribution is a component-level illustration that acquisition cost and total ownership cost can diverge sharply enough that the cheapest option and the lowest-total-cost option are different materials entirely: within the subset evaluated, the pathway with the highest estimated saving (mild steel to NM400) involves a grade priced above the material it replaces, with the saving generated substantially through fewer shutdowns — meaning procurement on lowest unit price can eliminate the winning option outright, not merely leave savings on the table.

The practical contribution lies in the four-step framework itself: environment classification (Table 1) provides the screening filter; technical benchmarking (Table 2, Figure 2) and MTC verification (Table 3) provide the grade-selection and quality-assurance tools; and the parametric TCO model (Table 4, Figures 3–4) shows which components carry a robust savings case and which require field validation. Two limitations bound this scope. First, the TCO model rests on three expert informants (an end-user operator and two equipment OEMs) corroborated against documentary records rather than a systematic multi-site survey, and the full 34-component dataset was not reproduced here, so the figures shown are an illustrative subset, not a validated site-wide total. Second, technical benchmarking relies on manufacturer "typical" catalogue-level values rather than independent laboratory testing; this is precisely why Table 3's MTC verification step is structural to the framework rather than incidental — it is the mechanism that converts a typical value into a defensible, batch-specific one. Future research should prioritise field validation of wear rates and downtime using the complete dataset — correcting for shared-shutdown overlap across simultaneously replaced components — extension to bauxite, nickel laterite, and tin mining, and a standardised MTC procurement checklist for the Indonesian supply environment.

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AUTHOR CONTRIBUTION STATEMENT

The corresponding author confirms sole authorship of this manuscript, including conceptualisation, methodology development, expert consultation, data analysis, writing, and review. No co-author contributions to declare.

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