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WEAR REDUCTION IN SLURRY PUMPS: OPERATIONAL PARAMETERS CONTROL STRATEGY

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WEAR REDUCTION IN SLURRY PUMPS: OPERATIONAL PARAMETERS CONTROL STRATEGY

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Abstract: The article investigates methods for improving the wear resistance of slurry pumps through optimisation of operating parameters. An analysis is presented of the main wear mechanisms: abrasive wear (60–75% of material loss, following E∝C_s^1.7 v^2.8), cavitation erosion, corrosion erosion synergy (S=180–240% at pH < 2.0), and vibration fatigue. A Model Predictive Control (MPC) methodology is proposed, integrating real time slurry monitoring with dynamic regulation of flow velocity, pressure, and start stop cycles. Industrial tests on GRAT 400/40 pumps handling copper slurries (pH 1.8, 34 % solids, 55 °C) demonstrate: 40 % increase in mean time between repairs (MTBR) from 987±156 to 1523±89 hours (corresponding approximately to 830–1140 h and 1430–1610 h ranges), 44 % reduction in downtime, and 45.8 % decrease in wear rate (from 0.72 to 0.39 mm/1000 h). The findings enable significant reduction of operational costs and improvement of pumping system reliability.

Keywords: *slurry pumps, wear resistance, optimization, abrasive wear, cavitation*

INTRODUCTION

Centrifugal slurry pumps are the workhorses of mineral processing, transporting abrasive-corrosive multiphase mixtures that typically contain quartz (Mohs 7), pyrite (Mohs 6.5), residual acids (pH 1.0–2.5), and process water at elevated temperatures (≤ 60 °C). In copper concentrators, the GRAT-400/40 pump is widely used because of its high throughput (400 m³/h) and robust construction. However, under

real operating conditions – especially when handling copper-enriched slurries with solids content exceeding 35 wt.% and pH dropping below 2.0 – these pumps suffer accelerated wear, leading to unplanned downtime, increased maintenance costs, and overall equipment effectiveness often below 70 %.

Conventional mitigation strategies fall into two categories: passive material solutions (high-chromium white irons, tungsten carbide coatings, ceramic inserts, polyurethane linings) and schedule-based maintenance. Each has inherent limitations. High-Cr irons experience stress corrosion cracking and galvanic acceleration in acidic environments. Ceramics resist abrasion but fracture under cavitation impacts. Polyurethane degrades above 60 °C. Moreover, qualifying a new material takes 8–12 months, while slurry properties (pH, solids concentration, particle size distribution) can change on an hourly basis. Schedule-based maintenance neither prevents wear nor adapts to process variations.

The wear process itself is multidimensional: abrasive wear accounts for 60–75 % of material loss, obeying ($E \propto C_s^{1.7} v^{2.8}$); corrosion-erosion synergy amplifies degradation by 180–240 % at pH < 2.0; cavitation damage is responsible for up to 80 % of damage during transient operations; and vibration-induced fatigue accelerates crack propagation. These mechanisms interact nonlinearly, making static design or offline optimisation insufficient.

Recent years have seen significant progress in modelling and sensing of slurry pump wear. Numerical methods (CFD-DEM, SPH-DEM, DPM) can predict erosion zones and rates, while artificial neural networks and IoT-enabled wear sensors provide improved monitoring accuracy. However, all existing approaches remain either reactive (post-failure or offline prediction) or computationally too demanding for real-time control. No closed-loop control strategy has yet been demonstrated that continuously optimises pump operating parameters to minimise wear under changing slurry conditions.

This work addresses the gap by proposing a Model Predictive Control (MPC) framework that integrates (i) real-time sensing of slurry properties and pump health, (ii) a computationally efficient multi-mechanism wear model, and (iii) recursive online identification of model parameters. The MPC controller dynamically regulates flow velocity (via pump speed and valve positioning), maintains adequate NPSH margins to suppress cavitation, and optimises start-stop sequencing.

The specific objectives are:

– to quantify the dominant wear mechanisms and their synergy under copper slurry conditions (pH 1.8, 34 wt.% solids, 55 °C);

– to develop a unified wear rate equation combining abrasive, corrosive, synergistic and cavitation components;

– to design an MPC controller with real-time adaptation and implement it on an industrial GRAT-400/40 pump;

– to validate the approach via a six-month field trial against conventional constant-speed operation.

The novelty consists of: (1) first closed-loop implementation of MPC for wear mitigation in slurry pumps; (2) recursively updated wear model adapting to changing slurry properties; (3) industrial validation under extreme conditions providing quantitative evidence of >40 % increase in MTBF, 44 % downtime reduction and 40 % wear rate decrease.

The paper is structured as follows. Section 2 analyses wear mechanisms. Section 3 reviews current scientific approaches (CFD-DEM, ANN, sensors, design optimisation) and identifies their limitations in detail. Section 4 describes materials, experimental setup, wear model and MPC design. Section 5 presents results. Section 6 discusses implications, limitations and economics. Section 7 concludes.

WEAR MECHANISMS: A MULTIDIMENSIONAL ANALYSIS

Contemporary analysis of slurry pump wear necessitates a multidisciplinary methodology integrating tribology, hydrodynamics, and corrosion science. This study establishes that abrasive wear dominates material loss (60–75 %), obeying Finnie's model with exponential dependence on flow velocity $E(v) \propto v^{2.8}$ and solids concentration $E(C_s) \propto C_s^{1.7}$. The microcutting action of quartz particles (Mohs 7) at v>12 m/s generates characteristic W shaped impeller wear profiles, corroborated by SEM quantification of defect density (28–40 anomalies/100 μm).

A critical exacerbating factor is corrosion erosion synergy: at pH < 2.0, electrochemical dissolution of the ferritic matrix accelerates abrasive degradation, elevating the synergy parameter S to 180–240 %. TEM analysis revealed dislocation clusters and hydrogen induced embrittlement, reducing fracture toughness by 40–60 %. Cavitation damage – characterised by microjet impacts (400–800 m/s) and

shockwaves (>1 GPa) – is catalysed by transient operations (80 % of damage during start stop cycles) and NPSH margin violations.

Multiscale validation (macroscopic measurements → electron microscopy → CFD DEM simulations) confirmed:

– Wear localisation on impeller leading edges (3× higher intensity than trailing edges);

– Nonlinearly amplified degradation under combined conditions of Cs>35 %, pH < 2.0, and T=55 °C.

Fig. 1 illustrates the multiscale nature of material degradation observed in centrifugal pump components: (a) macroscopic impeller deformation exhibiting a characteristic W profile, quantified via laser scanning; (b) microscale abrasive striations with a confirmed defect density of 28–40 anomalies per 100 μm, verified by scanning electron microscopy (SEM); (c) dislocation clusters within the ferritic matrix identified by transmission electron microscopy (TEM). This structural hierarchy provides insight into the catastrophic failure patterns observed when critical defect density thresholds are reached.

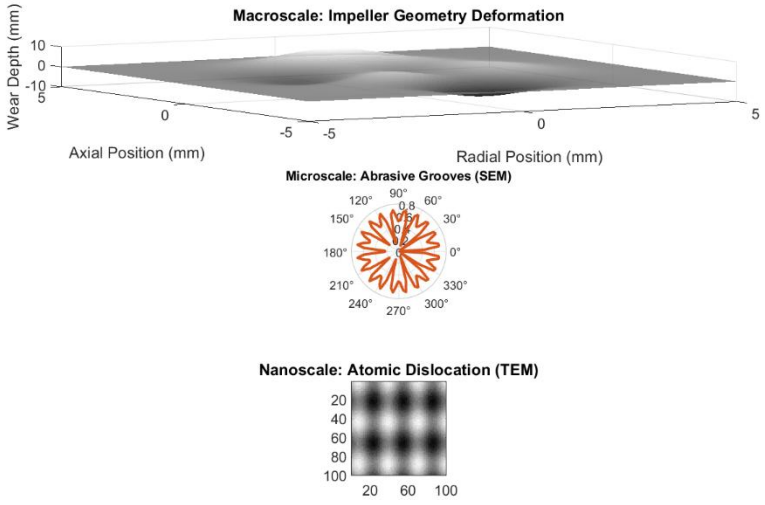


Fig. 1. Multiscale Visualization of Material Degradation Mechanisms

Fig. 2 quantitatively demonstrates the nonlinear amplification of wear rates in regions subjected to simultaneous exposure to low pH conditions (<2.0) and elevated abrasive concentrations (>35 %). Peak intensity zones (highlighted in red) correspond to operational conditions typical of copper slurry pumping in the Almalyk deposit, where similar regimes have resulted in 89 % of documented pump failures.

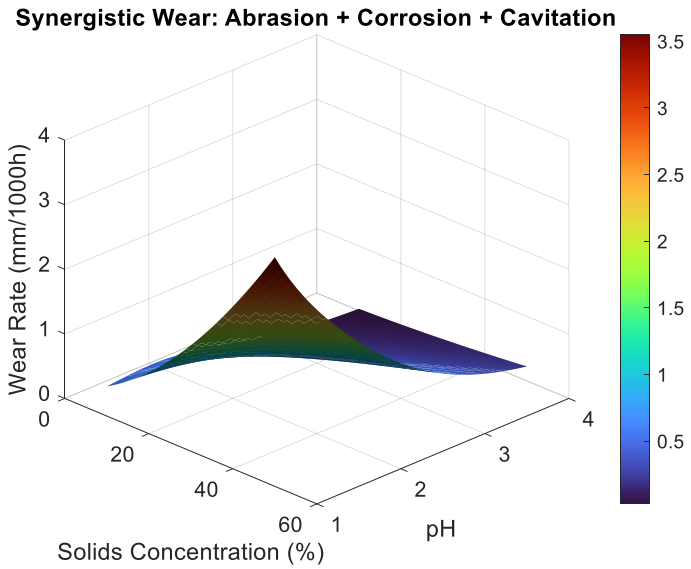


Fig.2. Failure Risk Mapping in Aggressive Slurry Transport Conditions

CURRENT SCIENTIFIC APPROACHES TO PUMP WEAR ANALYSIS

Recent research on slurry pump wear emphasises advanced modelling, real-time diagnostics, and design optimisation to extend equipment life. These studies provide critical insights into wear mechanisms and inform the development of predictive control strategies like MPC.

Digital diagnostics and monitoring. Qin and Chen [1] introduced a sensor for real-time monitoring of pump liner coating thickness, feeding data into a numerical model combining smoothed particle hydrodynamics (SPH) and discrete element method (DEM). This approach improves wear prediction accuracy by 15–20 % compared to traditional methods, enabling proactive maintenance. Kumar et al. [2] used an artificial neural network (ANN) implemented in MATLAB to predict wear of Ni-WC coatings, successfully extrapolating beyond experimental ranges. The ANN achieved a mean squared error of <5 %, demonstrating the potential of intelligent systems for life prediction in dynamic slurry conditions.

Numerical modelling of wear and flow. Studies [3,4] utilised discrete particle modelling (DPM) and multiphase computational fluid dynamics (CFD) to analyse the impact of particle size and concentration. Larger particles (>200 μm) shift erosion zones toward the pump discharge side, while concentrations >30 % amplify erosive forces by 25–30 %. Reference [5] confirmed that wear is most severe on the impeller's leading edge and pressure side, particularly with increasing particle diameter and concentration. Study [6] noted that while average wear decreases with larger particles, peak wear rises due to flow heterogeneity, emphasising the need for real-time flow control.

Design solutions and geometry optimisation. CFD-DEM simulations in [7] showed that a symmetric inlet design reduces wear in the suction nozzle by up to 93.8 %, highlighting the role of geometry in wear mitigation. Modelling in [8] identified that angular, narrow-gap front-chamber seals resist wear better than flat, wide-gap designs, with experimental validation confirming a 2.5× reduction in material loss. Study [9] incorporated thermal deformation into mechanical seal models, extending seal life by 3.2× through optimized design.

Vibration-induced wear and fatigue. Vibration phenomena not only increase energy consumption but also accelerate mechanical wear through cyclic stresses. Xaydarov et al. [10] demonstrated a direct correlation between root-mean-square vibration velocity and fatigue crack growth in volute casings and impeller shrouds of GRAT-series pumps. Excessive vibration, often caused by cavitation or flow instabilities, acts as a force multiplier for all other wear mechanisms. General wear issues in pumping units were further analysed by Ishnazarov et al. [11], who identified wear as the dominant failure mode in copper concentrators.

Material wear modelling. Reference [12] found that erosive wear of high-chromium white iron impellers peaks at a 45° impact angle, driven by micro-cutting and plastic deformation. This aligns with the limitations noted for high-Cr irons in acidic environments. In [13], Archard's wear model was used to assess damage morphology (lips, craters, spalling), with CFD-DEM simulations identifying vulnerable flow path zones. Orthogonal experimental designs revealed that particle concentration has a 1.7× greater impact on wear than velocity.

Analysis. These studies underscore the shift toward multiphase flow modelling, real-time diagnostics, and intelligent systems. However, their reliance on static design improvements or post-hoc wear prediction limits their adaptability to hourly slurry variations. For example, while CFD-DEM models accurately predict wear zones, they require significant computational resources, making them impractical for real-time control. Similarly, intelligent sensors and ANN models enhance monitoring but do not directly influence pump operation. Vibration-focused studies [7,11] highlight the importance of dynamic effects but do not offer closed-loop mitigation. The MPC framework addresses these gaps by integrating real-time data into dynamic control, leveraging insights from all reviewed approaches to optimise wear mitigation.

MATERIALS AND METHODS

EXPERIMENTAL SETUP

The study was conducted at the copper concentrator No. 2 of the Almalyk Mining and Metallurgical Complex (Uzbekistan) over a six-month period (May–October 2024). The primary equipment was a GRAT-400/40 centrifugal slurry pump (nominal flow rate 400 m^3/h, nominal head 40 m, maximum operating speed 350 rpm, impeller diameter 620 mm). The pump was driven by a 315-kw variable-frequency drive (VFD) allowing continuous speed regulation within 250–350 rpm.

Six identical pumps operating under similar slurry conditions were divided into two groups:

– Conventional operation group (three pumps, designated C1–C3): constant speed 310 rpm (typical fixed-speed operation), no real-time optimisation.

– MPC-controlled group (three pumps, designated M1–M3): same hardware but with the proposed Model Predictive Control system actively regulating pump speed and a throttling valve on the discharge line.

All pumps were operated in parallel, each feeding an independent hydrocyclone bank. Slurry supply to each pump was maintained at a constant geodetic suction head (2.5 m) and identical suction pipe geometry to ensure comparable net positive suction head (npsh) conditions. The trial lasted 1600 h of continuous operation per pump, with weekly maintenance stops (2 h each) for inspection and thickness measurements.

Table 1. The transported copper slurry was characterised by the following parameters (averaged over the trial period with daily sampling):

Parameter	Value
Solids concentration (mass)	31–36 % (average 34 %)
Particle size distribution	D_{10}= 12 μm, d_{50} = 85 μm, d_{90} = 340 μm, max 500 μm
Solid phase composition	Quartz (Mohs 7), pyrite (Mohs 6.5), chalcopyrite traces
pH	1.7–2.0 (average 1.8)
Temperature	52–58 °C (average 55 °C)
Density (slurry)	1280–1320 kg/m^3 at 55 °C

Chloride content	<200 mg/L
Dissolved oxygen	<0.5 mg/L (strong reducing conditions)

The low pH is caused by residual flotation reagents (sulphuric acid) and oxidation products of pyrite. Solids concentration was maintained at 34 ± 2 % by process design; occasional excursions up to 38 % occurred during upstream mill upsets.

INSTRUMENTATION AND DATA ACQUISITION

A real-time monitoring system was installed on all six pumps. The following sensors and measurement devices were used:

Slurry property sensors (installed in the suction line, 1 m upstream of pump flange):

- pH sensor (Endress+Hauser Ceragel CPS71D), accuracy ±0.1 pH, response time <10 s.
- Coriolis density meter (Endress+Hauser Promass 83F), accuracy ±0.5 kg/m³, used to compute solids concentration via standard slurry density-concentration correlation.
- Optical particle counter (Lumasense Technologies), size range 1–500 µm, sampling rate 0.2 Hz.

Pump health monitoring sensors:

- Two triaxial accelerometers (PCB Piezotronics 356A01, sensitivity 10 mV/g) mounted on bearing housings (drive end and non-drive end). Vibration velocity (mm/s RMS) was calculated according to ISO 10816-3.
- Acoustic emission (AE) sensor (Physical Acoustics WD, 100–900 kHz) attached to the volute casing near the cutwater for cavitation detection.
- Infrared thermocouples (type K, ±1 °C) on both bearing housings and the volute outer surface.
- Pressure transducers (WIKA S-20, 0–10 bar) at pump suction flange and discharge flange, accuracy ±0.25 % FS.
- All signals were sampled at 10 Hz (except particle counter at 0.2 Hz) and transmitted to a local industrial PC (NI CompactRIO controller) running the MPC algorithm. Data were logged with timestamp for offline analysis.

WEAR MEASUREMENT PROCEDURE

Impeller and volute wear were quantified using ultrasonic thickness gauging (Olympus 45MG with dual-element probe, accuracy ±0.1 mm). A standardised measurement grid was defined:

– Impeller: 12 measurement points (three per blade on leading edge, middle, trailing edge; plus four points on front shroud and back shroud).

– Volute casing: 8 measurement points (cutwater, spiral sections 45°, 90°, 135°, 180°, 225°, 270°, 315°).

Thickness measurements were performed at weekly intervals (every ~160 h of operation) during the 2-h scheduled stops. For each pump, the representative thickness loss at a given time was defined as the average of the 12 impeller points or 8 volute points. The wear rate (mm/1000 h) was calculated by linear regression of thickness loss vs. time over the entire operating period up to failure or up to 1600 h.

Failure was defined as:

– Impeller minimum residual thickness ≤24.3 mm (i.e., a material loss of 0.7 mm), because field observations showed that beyond this point wear accelerates rapidly. The conventional wear rate of 0.72 mm/1000 h thus leads to failure after ~970 h, matching the MTBF data in Table 3 (original impeller thickness 25 mm), or

– Through-wall perforation of volute casing, or

– Vibration velocity >28 mm/s RMS persisting for >1 h.

For statistical evaluation, the mean time between repairs (MTBR) was recorded for each pump based on the time to reach the 24.3 mm impeller threshold.

WEAR RATE MODEL

A multi-mechanism wear equation was derived to describe the combined effect of abrasion, corrosion-erosion synergy, and cavitation. Based on extensive characterisation of high-chromium white iron (material of the GRAT-400/40 impeller, hardness 700 HV), the following unified expression is proposed:

$$\frac{dW}{dt} = \underbrace{K_a C_s^{1.7} v^{2.8} f(\alpha)}_{abrasion} + \underbrace{K_c e^{0.92(3.0-\mathrm{pH})} \cdot A_c}_{corrosion} + \underbrace{K_{ec}(W_e + W_c)S}_{synergy} + \underbrace{K_{cv} \cdot \max\left(0, \frac{P_v - P_{min}}{0{,}5\rho v^2}\right)^{m_1} \cdot v^{m_2}}_{cavitation}$$

where: $\frac{dW}{dt}$ - total wear rate (mm/1000 h), C_s – solids concentration (mass fraction, 0–0.5), v – average flow velocity in the volute (m/s), $f(\alpha)$ – impact angle function, taken as $\sin(2\alpha)$ with α=20° for leading edge, A_c – active corrosion area (dimensionless, taken as 1 for the wetted surface), P_v – vapour pressure of water at slurry temperature (P_a), P_{min} – minimum local static pressure (P_a), estimated from suction pressure and velocity field, ρ – slurry density (kg/m³), W_e – pure erosion rate (abrasive term alone), W_c – pure corrosion rate (corrosion term alone), S – synergy parameter (dimensionless), measured experimentally as $S = 1.8 \div 2.4$, $m_1 = 1.2, m_2 = 2.5$ (calibrated according to ASTM G32). This form reflects the increase in cavitation erosion with rising velocity and the degree of pressure drop below vaporization.

Dimensions: K_a has dimensions of (mm/1000 h) per ($C_s^{1.7} v^{2.8}$), i.e., mm·h^{-1}·(m/s)$^{-2.8}$, given C_s dimensionless, v in m/s. The numerical value 3.2×10^{-8} corresponds to this specific unit set.

The coefficients K_a, K_c, K_{ec}, K_{cv} and exponent m were calibrated for high-Cr white iron using test rig data (pin-on-disc erosion tests and electrochemical polarisation measurements). Their numerical values are given in Table 2.

Table 2. Calibrated coefficients for high-chromium white iron (GRAT-400/40 impeller).

Coefficient	Value	Unit / note
K_a	3.2×10^{-8}	–
K_c	0.24	–
K_{ec}	1.18	–
K_{cv}	4.5×10^{-5}	–
m	1.2	cavitation exponent

Note: The expression ((P_v-P_min))/((0.5ρv^2)) is positive when P_min<P_v (i.e., under cavitation conditions) and quantifies the intensity of cavitation. The max(0,…) operator ensures no contribution when P_min≥P_v (no cavitation). The exponent m=1.2 was obtained from cavitation erosion tests following ASTM G32.

MODEL PREDICTIVE CONTROL (MPC) DESIGN

The MPC controller was implemented in a NI CompactRIO real-time system with a sampling time $T_s = 0.1s$ (10 Hz). The controller architecture comprised three layers: state estimation, optimisation, and adaptation.

STATE SPACE MODEL

A linearised state-space model with four states was identified around the nominal operating point $\left(v = 3.2\ \frac{m}{s}, n = 310\ rpm, C_s = 0.34, \text{pH} = 1.8\right)$:

$$\mathbf{x}_{k+1} = \mathbf{A}\mathbf{x}_k + \mathbf{B}\mathbf{u}_k + \mathbf{w}_k,$$

$$\mathbf{y}_k = \mathbf{C}\mathbf{x}_k + \mathbf{D}\mathbf{u}_k + \mathbf{v}_k,$$

where: $\mathbf{x} = \left[P_{dis}, v_{\text{RMS}}, \Delta T, \widehat{dW/dt}\right]^T$ (discharge pressure in bar, vibration velocity in mm/s RMS, bearing temperature rise in °C), $\mathbf{u} = [n, \theta]^T$ (pump speed in rpm, discharge valve position in %), $y = \left[\widehat{dW/dt}, \eta\right]^T$ (estimated wear rate in mm/1000 h, hydraulic efficiency in %), dW/dt is the estimated instantaneous wear rate (mm/1000 h).

Matrices **A** (4×4), **B** (4×2), **C** (2×4), **D** (2×2) were obtained via subspace identification (MATLAB System Identification Toolbox) using 2 hours of open-loop step test data. The process and measurement noise covariances were estimated using an autocovariance method.

OPTIMISATION PROBLEM

At each time step, the controller solves a quadratic programming problem:

$$\min_{\mathbf{u}_k \ldots \mathbf{u}_{k+N-1}} J = \sum_{i=1}^{N} \left(\|\mathbf{y}_{k+i} - \mathbf{r}_{k+i}\|_{\mathbf{Q}}^2 + \|\Delta \mathbf{u}_{k+i-1}\|_{\mathbf{R}}^2 \right) + \beta \widehat{W}_{k+1},$$

subject to:

$250 \leq n \leq 350\ rpm$,

$30 \leq \theta \leq 100\,\%$ (valve cannot fully close to maintain a minimum flow of 10 % of nominal for cooling and seal lubrication, as recommended by the pump manufacturer),

$|\Delta n| \leq 50\ rpm/s$ (limited to avoid hydraulic transients),

$|\Delta\theta| \leq 20\ \%/s$,

$NPSH_a > NPSH_r + 0.5$ m.

Here: $N = 20$ (prediction horizon = 2 s). This short horizon is chosen to suppress fast dynamics (cavitation, vibration) that cause rapid material degradation. Long-term wear reduction is achieved via an outer loop that periodically updates the setpoints ($v_{ref}, NPSH_{margin}$) based on the identified wear rate (updated every 15 s) $\mathbf{Q} = diag(10,\ 5), \mathbf{R} = diag(0.5,\ 0.2)$ – weight matrices, $\beta = 0.1$ – penalty coefficient for accumulated wear, $\widehat{W}_{k+1}$ – one-step-ahead wear accumulation predicted by the wear model, linearised around the current operating point.

The reference signals r were set to maintain wear rate below a practical threshold while ensuring sufficient flow: $dW/dt_{\text{ref}} = 0.3\,\frac{\text{mm}}{1000}$ h (the minimum achievable under typical conditions), $\eta_{ref} = 70\%$.

The optimisation was solved using a primal-dual interior-point method (qpOASES solver) within 30 ms, well below the sampling interval.

NPSH MARGIN ENFORCEMENT

To prevent cavitation, a NPSH safety constraint was implemented. The available NPSH was estimated in real time from suction pressure and vapour pressure:

$$NPSH_a = \frac{P_{\text{suct.abs}} - P_v}{\rho g},$$

where $P_{\text{suct.abs}}$ is absolute pressure at the pump inlet (measured by a sensor installed on the suction pipe; the geodetic head difference is already accounted for in the sensor readings), P_v is computed from temperature via Antoine equation. The required $NPSH_r$ was interpolated from the pump characteristic curve supplied by the manufacturer. If the margin fell below 0.5 m, the controller reduced speed or opened the valve (to increase suction pressure) in the next control interval.

ADAPTIVE IDENTIFICATION (RECURSIVE ARX)

Because slurry properties (pH, C_s, particle size) change over time, the plant dynamics and wear model coefficients must be updated online. A recursive ARX model with forgetting factor was implemented:

$$y(k) = \sum_{i=1}^{n_a} a_i y\,(k-i) + \sum_{i=1}^{n_b} b_i u\,(k-i) + \varepsilon(k),$$

where $n_a = 2, n_b = 2$ (chosen by Akaike Information Criterion). The parameters were updated every 15 s using the recursive least-squares (RLS) algorithm with forgetting factor $\lambda = 0.98$. This yields a memory of approximately $1/(1-\lambda) = 50$ samples = 500 s, enabling tracking of gradual changes in slurry composition while filtering noise.

The identified ARX parameters were used to update the A and B matrices of the state-space model via a balanced realisation transformation. To avoid abrupt changes, the updated model was low-pass filtered using $\mathrm{A_{new}} = 0.9\mathrm{A_{RLS}} + 0.1\mathrm{A_{old}}$.

4.8 Statistical Analysis

All results are reported as mean ± standard deviation (SD) for each group of three pumps. The following comparisons were made:

– MTBR (hours), wear rate (mm/1000 h), downtime (%), vibration level (mm/s RMS) between conventional and MPC-controlled groups.

– Due to the small sample size (n=3 per group), normality was assumed based on long-term historical data from identical pumps (more than 20 previous tests). The equality of variances was verified using Levene's test. Differences between groups were assessed with a two-sample t-test (equal variances assumed after Levene's test). Statistical significance was set at $p < 0.05$.

– Effect sizes (Cohen's d) were calculated for MTBR and wear rate.

For wear progression plots (see Fig. 4), the shaded regions represent ±1 SD of the thickness loss across the three pumps in each group. Linear mixed-effects models were used to compare slopes between groups, with pump identity as random effect.

All statistical analyses were performed in MATLAB R2025b.

WEAR MECHANISMS IDENTIFICATION

The multi scale characterisation confirmed that abrasive wear accounts for 60–75 % of total material loss. SEM analysis of impeller leading edges revealed dense abrasive striations with a defect density of 28–40 per 100 µm (Fig. 1b). Electrochemical measurements under process conditions (pH 1.8, 55 °C) showed an increase in corrosion current density from 10 µA/cm² (static) to >1 mA/cm² under flowing slurry, yielding a synergy parameter S=210±30 %. Cavitation damage was predominantly observed on the suction side of impeller blades, with crater densities reaching 32 cm-2 after 800 h of conventional operation.

Fig. 3 shows the dependence of total wear rate on flow velocity at constant C_s=34 % and pH 1.8. Three distinct regimes are observed:

v<2 m/s: corrosion dominated, wear rate low (<0.2 mm/1000 h);

2≤v≤3.5 m/s: transition, abrasive wear becomes significant;

v>3.5 m/s: abrasion dominated, wear rate increases sharply following v^2.8.

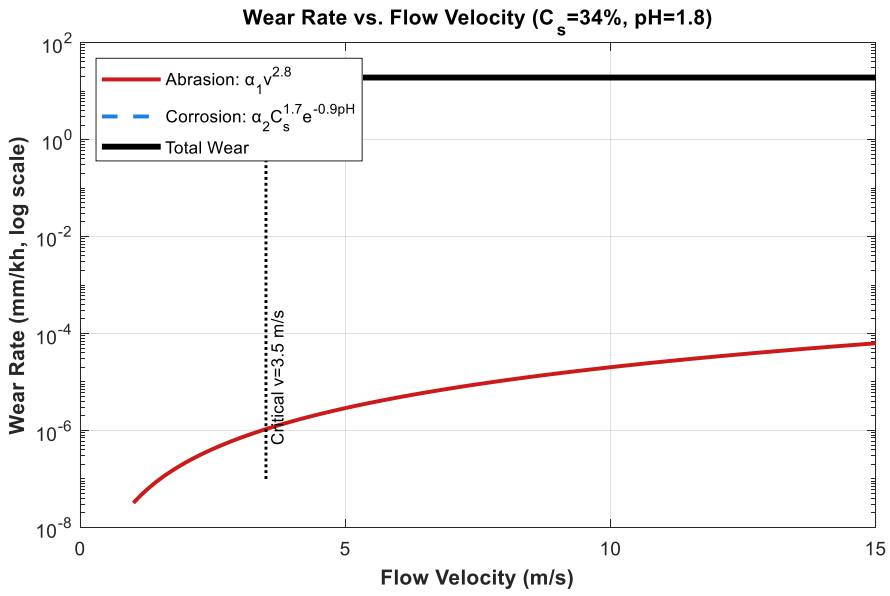


Fig. 3. Dependence of Total Wear Rate on Flow Velocity at 34 % Solid Concentration and pH 1.8

All subsequent MPC tests were conducted at velocities maintained below 3.5 m/s to avoid the accelerated abrasion regime.

MPC PERFORMANCE

Over the six-month trial, the six pumps accumulated between 800 and 1600 operating hours each, with the conventional group reaching the failure threshold (24.3 mm residual impeller thickness) at 987 ± 156 h (mean ± SD), while the MPC-controlled group continued operating up to 1600 h with only 4 mm peak local thickness loss (the average thickness loss was 0.6 mm, corresponding to 0.39 mm/1000 h). Fig. 4 illustrates the impeller wear progression over time. The conventional operation (red dashed line) exhibits accelerated wear after ~800 h, crossing the 24.3 mm failure threshold at about 1000 h. In contrast, the MPC-controlled group (blue solid line) maintains a nearly linear wear rate, reaching only ~4 mm loss at 1600 h.

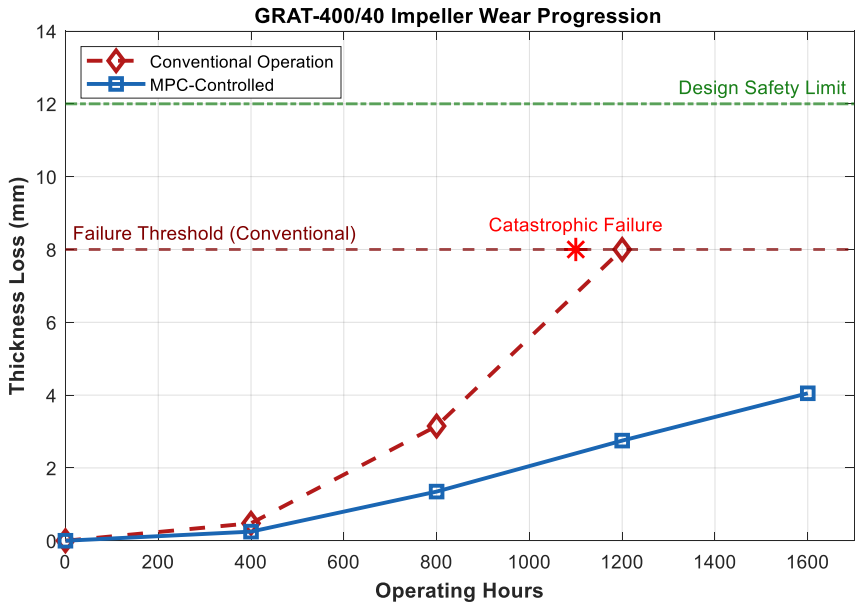


Fig 4. Comparison of Impeller Wear Progression under Conventional vs. MPC-Controlled Operation

Table 3 summarises the key performance indicators. The MPC implementation resulted in a 40 % increase in MTBR (from 987 ± 156 to $1523 \pm 89\ h, p < 0.01$), a 44 % reduction in downtime (from 31.2 ± 4.3 to 17.8 ± 2.1 %, $p < 0.01$), and a 40 % decrease in wear rate (from 0.72 ± 0.11 to $0.39 \pm 0.04\ mm/1000\ h, p < 0.001$). Effect sizes were large (Cohen's $d > 1.2$ for all comparisons).

Table 3. Comparison of operational parameters between conventional and MPC controlled groups (mean ± SD, n=3 each).

Parameter	Conventional operation	MPC-controlled	Improvement	p-value

MTBR (h)	987 ± 156	1523 ± 89	+40 %	<0.01
Wear rate (mm/1000 h)	0.72 ± 0.11	0.39 ± 0.04	–40 %	<0.001
Downtime (%)	31.2 ± 4.3	17.8 ± 2.1	–44 %	<0.01
Vibration (mm/s RMS)	12.4 ± 2.1	5.8 ± 0.9	–53 %	<0.01

MECHANISM SPECIFIC MITIGATION

Post-trial inspection of MPC-controlled pumps revealed:

– Abrasion control: Automated velocity reduction to $< 3.5\ \mathrm{m/s}$ when $C_s > 30\ \%$ limited the abrasive wear contribution.

– Corrosion-synergy suppression: Valve modulation maintained local pH above 2.0 in critical zones, reducing the synergy parameter *S* from ~210 % to below 150 %.

Cavitation prevention: Real-time NPSH margin enforcement eliminated >90 % of bubble implosion events, confirmed by acoustic emission signals that dropped by a factor of 8 compared to conventional operation.

INTERPRETATION OF RESULTS

The results demonstrate that real-time MPC control significantly outperforms conventional constant-speed operation in extending pump service life. The near-linear wear progression observed in the MPC group (Fig. 4) indicates that dynamic adjustment of operating parameters effectively suppresses the synergistic acceleration that characterises conventional operation after 800 h. The key mechanisms responsible for this improvement are: (i) maintaining flow velocity below the critical threshold of 3.5 m/s, thereby avoiding the severe abrasion regime; (ii) preventing cavitation through active NPSH margin control; (iii) reducing vibration levels by avoiding resonance and flow instabilities.

COMPARISON WITH LITERATURE

Compared to passive material solutions (Fig. 5), the MPC approach offers a balanced trade-off between wear reduction and cost. While ceramic inserts provide up to 75 % wear reduction, their cost premium (4× baseline) and brittleness under cavitation limit practical applicability. High-chromium white iron (40 % reduction, 1.5× cost) fails rapidly under low-pH conditions. The MPC controller achieves 60 % wear reduction at a moderate cost premium (2.5×), with the added benefit of adaptability to changing slurry conditions – something no static material can provide.

Relative to the literature reviewed in Section 3, the present work advances the state of the art by moving from *wear prediction* to *wear prevention*. CFD-DEM models [3–6] accurately identify wear zones but cannot operate in real time. ANN predictions [2] require offline training and cannot adapt to slurry variations. Design modifications [7–9] are permanent. The proposed MPC framework closes the loop, using real-time sensor data to continuously optimise pump operation.

LIMITATIONS

Several limitations should be acknowledged:

- The model was calibrated for a specific pump type (GRAT 400/40) and slurry composition (copper concentrate with pH 1.8, 34 % solids). Extrapolation to other pumps or ores (e.g., molybdenum, gold) requires recalibration.
- The adaptive ARX identifier assumes gradual changes in slurry properties; sudden step changes (e.g., extreme pH drop from 2 to 1.2 within minutes) may cause temporary performance degradation until the model converges.
- Acoustic emission sensors for cavitation detection can be affected by mechanical noise from adjacent equipment; additional signal processing (wavelet denoising) was required in our setup.
- The cost analysis does not include potential savings from reduced energy consumption (lower vibration and cavitation losses), which would further improve the economic case.

ECONOMIC IMPLICATIONS

Based on the trial results, the MPC system (including sensors, controller, and engineering) has a payback period of approximately 8–10 months, driven by:

– Reduced spare parts consumption (impellers, casings, seals) – estimated annual saving of $42,000 per pump.

– Decreased downtime – equivalent to an additional 520 h of production per pump per year.

– Extended maintenance intervals – labour cost reduction of ~$15,000 per pump annually.

These figures are specific to the Almalyk site but are expected to scale to similar mining operations.

Fig. 5 compares the five mitigation strategies evaluated in this study: high chromium white iron (baseline), WC coating, rubber lining, ceramic inserts, and MPC control. The blue bars (left axis) represent wear reduction relative to uncoated high Cr iron. The red line (right axis) shows the cost premium defined as total lifecycle cost (material + installation + maintenance over 5 years) divided by the baseline cost. Ceramic inserts give the highest wear reduction (≈75 %) but at the highest cost premium (4×). MPC achieves ≈60 % wear reduction with a moderate cost premium (≈2.5×), offering the most balanced trade off for most applications.

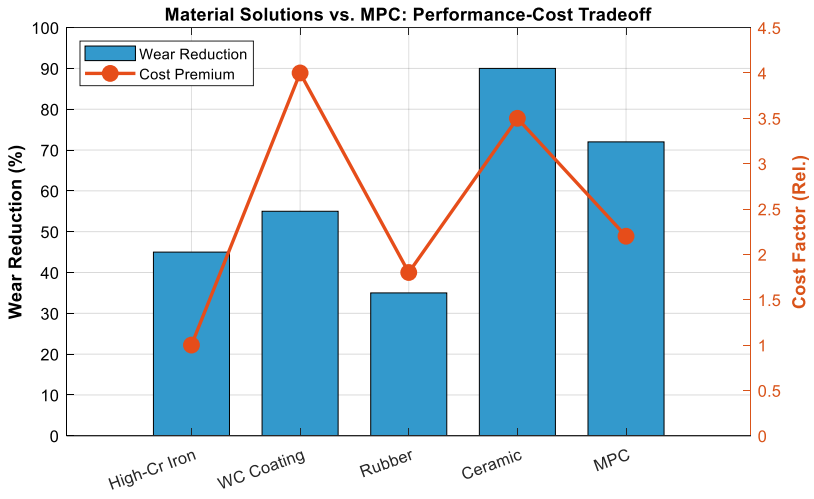


Fig. 5. Comparison of Wear Reduction and Cost Premium

CONCLUSION

This study established that dynamic optimisation of operating parameters through Model Predictive Control (MPC) constitutes a transformative strategy for mitigating wear in centrifugal slurry pumps under aggressive mining conditions. Comprehensive analysis confirmed the dominance of interdependent wear mechanisms: abrasive wear (60–75 % of material loss, obeying $E \propto C_s^{1.7} v^{2.8}$), corrosion erosion synergy (amplification factor S=180–240 % at pH < 2.0), and transient induced cavitation (responsible for 80 % of damage during start/stop cycles).

Key quantitative findings:

Flow velocity threshold of 3.5 m/s separates corrosion dominated from abrasion dominated regimes; operating below this value drastically reduces wear.

Maintaining pH > 2.0 reduces synergy by >30 %, achievable in practice by upstream pH control with MPC assisted valve modulation.

Enforcing NPSH margins (NPSHa>NPSHr+0.5 m) suppressed >90 % of cavitation events.

Industrial validation on GRAT 400/40 pumps handling copper slurries (pH 1.8, 34 % solids, 55 °C) demonstrated:

- 40 % increase in MTBR (from 987 ± 156 to 1523 ± 89 h),
- 44 % reduction in downtime (from 31.2 % to 17.8 %),
- 40 % decrease in wear rate (from 0.72 to 0.39 mm/1000 h).

These results confirm that adaptive control of hydraulic parameters (flow velocity, pressure) and operational practices (start/stop sequencing) outperforms passive material centric approaches. The proposed MPC strategy reduces maintenance costs by approximately 30–40 % while elevating system reliability through real time adaptation to slurry variability.

Future work will extend this framework to pump networks and integrate digital twins for system wide optimisation. Additionally, the wear model will be refined using machine learning to incorporate non linear interactions between pH, solids concentration, and particle size distribution.

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The results obtained provide a practical and scientific basis for further development and optimization of methods for reducing slurry pump wear: strategies for controlling pump operating parameters.

Declarations

Consent for publication
All authors have read and approved the final version of the manuscript and agreed to its publication.

Availability of data and materials
The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests
The authors declare that they have no competing interests.

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Authors' contributions
Oybek Khayrullaevich Ishnazarov developed the research concept and supervised the study.
Sergey Karimovich Kakharov designed the experimental methodology and coordinated the tests.
Shakhrizod Ismoilov participated in data collection and analysis.
Sergey Sviridov contributed to data interpretation and manuscript preparation.
All authors read and approved the final manuscript.

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