



Technische  
Universität  
Braunschweig



## Project-Proposal

# AI-powered Milling Expert System for Industrial Application

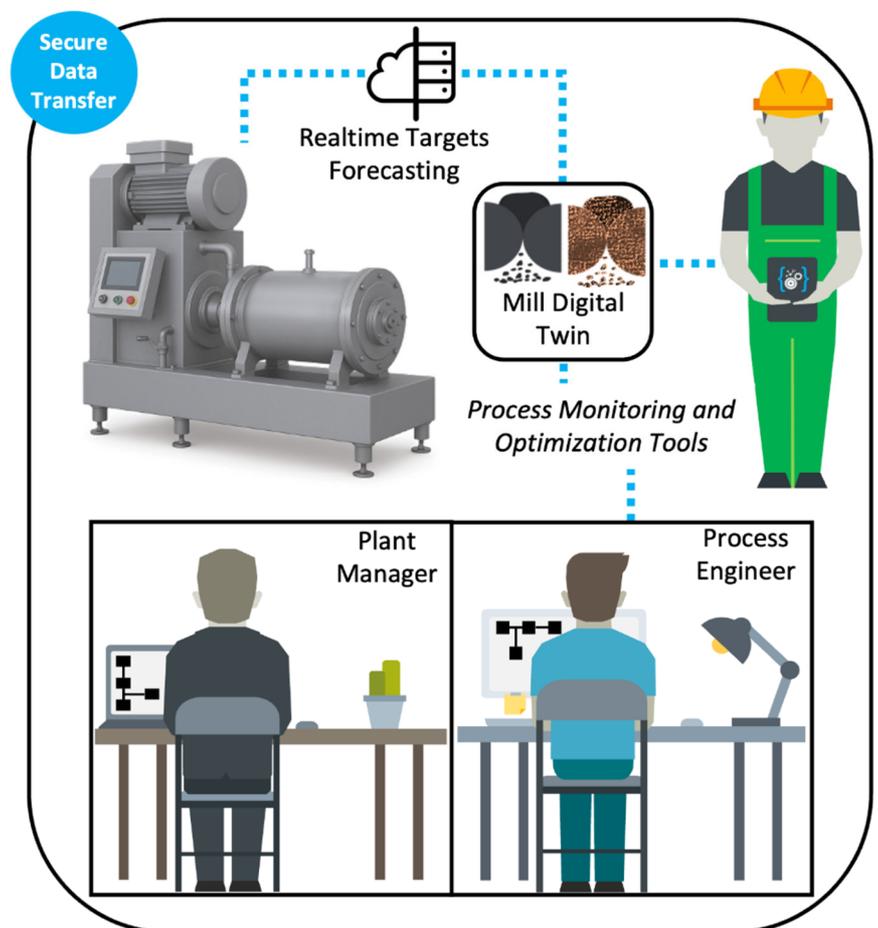
PREPARED FOR

**INTERNATIONAL FINE PARTICLE RESEARCH INSTITUTE  
(IFPRI)**

PREPARED BY

**INSTITUTE FOR  
PARTICLE  
TECHNOLOGY  
TU BRAUNSCHWEIG**

PROF. CARSTEN  
SCHILDE



## TABLE OF CONTENTS

<b>1.</b>	<b>INTRODUCTION AND MOTIVATION .....</b>	<b>3</b>
<b>2.</b>	<b>OBJECTIVES AND PROJECT SCOPE .....</b>	<b>5</b>
<b>2.1</b>	<b>PROJECT SCOPE .....</b>	<b>5</b>
<b>2.2</b>	<b>SCOPE BOUNDARIES .....</b>	<b>5</b>
<b>3.</b>	<b>CORE MODELING FRAMEWORK AND INDUSTRIAL RELEVANCE .....</b>	<b>6</b>
<b>3.1</b>	<b>WORKFLOW OVERVIEW .....</b>	<b>6</b>
<b>3.2</b>	<b>INDUSTRIAL USE CASES .....</b>	<b>6</b>
<b>3.3</b>	<b>EXPECTED IMPACT .....</b>	<b>7</b>
<b>4.</b>	<b>WORK PLAN AND DELIVERABLES .....</b>	<b>7</b>
<b>5.</b>	<b>COLLABORATION AND DATA STRATEGY .....</b>	<b>8</b>
<b>6.</b>	<b>EXPECTED OUTCOMES AND INDUSTRIAL BENEFITS .....</b>	<b>8</b>
<b>7.</b>	<b>FINANCING .....</b>	<b>8</b>

# 1. INTRODUCTION AND MOTIVATION

Efficient and reliable fine comminution remains a fundamental challenge in particle technology and process engineering. Across diverse industries such as catalysts, ceramics, pigments, and minerals, the performance of comminution mills and classifiers directly determines product quality, throughput, and energy efficiency. Despite decades of progress, the design and operation of comminution machines and circuits with classifiers are still often guided by empirical rules of thumb, operator experience, and laborious trial-and-error adjustments rather than by systematic, model-based optimization.

Modern plants are increasingly equipped with sensors that measure torque, power draw, slurry temperature, and/or other product-related key variables (e.g. on-/in-/at-line measurement of particle sizes/size distributions). The data generated by these systems, however, are frequently underutilized. Engineers may collect and visualize process signals, but they rarely have access to integrated tools that link those measurements with mechanistic models or advanced analytics. As a result, critical opportunities for process understanding and optimization remain untapped. Engineers lack robust means to conduct “what-if” analyses, diagnose performance deviations, or quantify efficiency losses with confidence (Figure 1).

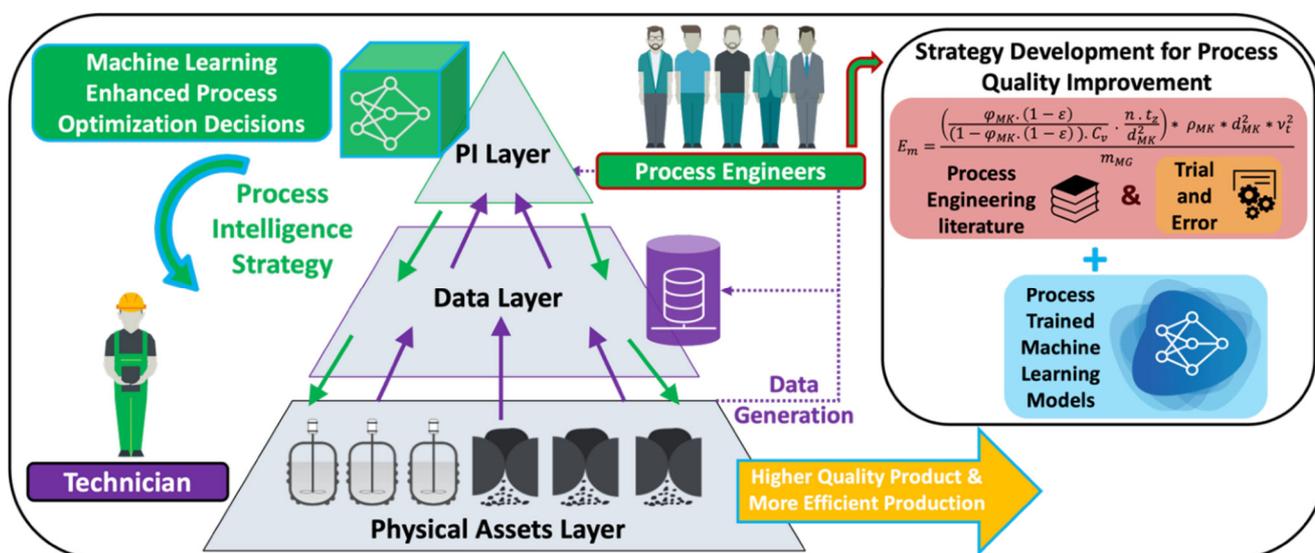


Figure 1: Process Intelligence Strategy: Integration of Physical Assets, Data Layers, Process Engineers, and AI for Smarter Comminution Operations.

To address this gap, the proposed project introduces a hybrid AI comminution platform that combines established comminution models with modern data analytics, visualization, and machine learning capabilities. The platform will function both as a simulation engine and as a real-time decision-support dashboard, enabling process engineers to analyze, visualize, and optimize comminution operations in an intuitive way. In this context, the project will also highlight the potential of AI to improve process understanding, predictive accuracy, and operational decision-making. In a forward-looking perspective, the project will additionally outline the potential for future AI-driven control solutions, demonstrating how advanced models could eventually support or automate operational adjustments in comminution circuits. At the same time, it will outline the necessary prerequisites for a reliable AI application, including sufficient data quality and coverage, appropriate sensor signals, consistent process operation, and robust model validation strategies. These aspects provide a realistic framework for assessing where and how AI methods can add value in industrial comminution processes. The envisioned software environment will include three central components:

1. **Model Library** that provides physics-based comminution and classification models, e.g. including Kwade’s stress model, Tavares breakage model, Population Balance Models (PBM), classical energy–size relationships, etc.

2. **Process Dashboard** that connects to live plant data or offline datasets and visualizes key performance indicators (KPIs) such as power draw, throughput, and particle size development. Unlike standard OM dashboards (e.g., WinCC), it also displays parameters predicted by integrated ML models and values computed from embedded empirical or mechanistic models, providing process-specific insights beyond conventional monitoring tools.
3. **Hybrid AI Module** that demonstrates how machine learning can complement mechanistic models to improve calibration, predictive accuracy, and adaptability to plant-specific conditions.

A fundamental version of the platform has already been developed in a rudimentary form; however, the mechanistic models and AI-based tools required for transferring the approach to other mills and processes, as well as for enabling advanced optimization and monitoring functionalities, still need to be established and subsequently integrated into an initial demonstrative implementation.

Beyond the initial open-source release, the project aims to create a fundamental platform that is openly available and will serve as a shared technological foundation for advanced process intelligence in fine comminution. The core purpose of the platform is to provide a unified environment in which mechanistic models, data-visualisation tools, and hybrid AI routines can be combined to simulate, analyse, and understand comminution processes. This modular structure enables the community to extend and refine the models collaboratively and offers a scalable basis for developing process-specific digital twins and advanced optimisation strategies in subsequent projects. A central element of the concept is the clear pathway for industrial extension. In the first phase, this will be demonstrated using generic model processes, which can later be adapted and expanded to specific industrial applications. IFPRI member companies can, if desired, securely integrate their own process data in follow-up projects, supported by the project team where needed, to develop plant-specific digital twins within the same framework and create plant-specific digital twins within the same framework. Enhanced by machine learning, these digital twins will capture the unique operating characteristics of each plant and provide real-time predictions of PSD evolution and energy efficiency. Crucially, this customisation without requiring companies to disclose their process or production data externally; partner-specific data are only used when a company explicitly chooses to provide them. This allows the advantages of data-driven methods to be realised fully while avoiding the confidentiality risks that often limit cross-company model development. To address challenges such as feed variability or the introduction of new materials for the comminution process, the platform will incorporate machine learning approaches and ensemble learning methods. These methods will accelerate the adoption of new models by combining mechanistic insights with data-driven learning, enabling continuous improvement when online data from participating plants are made available. Additionally, multiparameter optimisation routines will be implemented to generate actionable strategies for process optimisation. The performance of the platform in process prediction and optimization will ultimately depend on the availability and structure of company-specific data, the feasibility of securely connecting these data streams, the complexity of the underlying processes and formulations, and the extent to which mechanistic knowledge from the literature can be applied to the system in question. In this context, it is anticipated that company-specific adaptation of the platform will be essential to unlock its full potential for each individual operation.

The resulting two-level structure consists of an open, pre-competitive foundation, alongside company-specific, private extensions. Together, these ensure transparency and industrial relevance. Phase 1 will deliver the shared foundation in the form of an open-source platform. Phase 2 will enable companies to securely integrate their own data streams and digital interfaces for continuous plant monitoring in subsequent projects, allowing them to create proprietary extensions. This approach is fully consistent with IFPRI's mission to foster collaborative, pre-competitive research, enabling its members to achieve tangible industrial benefits. The expected outcome is a transparent, extensible and practical digital tool that will empower engineers to understand, simulate and optimise comminution performance more effectively than before, providing a secure basis for the scalable digital transformation of fine-particle manufacturing.

## 2. OBJECTIVES AND PROJECT SCOPE

The overall objective of the project is to design, develop, and validate an open-source AI platform for comminution processes. The platform will integrate mechanistic models, live data visualization, and advanced AI routines in order to strengthen process understanding, facilitate systematic troubleshooting, and support the optimization of industrial operations. In pursuing this objective, the project aims to create an open and modular software environment that incorporates a broad range of established comminution models, e.g. Kwade's stress model (e.g. for energy benchmarking, scaling, optimization.), Tavares breakage model (e.g. for predicting PSD(t),  $d_{50}$  evolution, comminution kinetics.), classification models (e.g. for optimizing classification efficiency and recycle ratio), and classical energy–size relationships, etc. Together, these models will form a comprehensive theoretical backbone for the simulation and analysis of comminution systems.

Another important objective is the development of a process dashboard that enables monitoring and benchmarking of industrial operations. The dashboard will be capable of connecting to real-time plant data as well as offline datasets, and it will provide visualization and estimation of key performance indicators such as power draw, stress intensity, throughput, particle size distribution, and overall energy efficiency, including AI-based analysis of dynamic process relationships. The project will also demonstrate a machine learning modeling workflow in which mechanistic equations are combined with machine learning components. This approach will enhance predictive accuracy and improve parameter calibration, thereby bridging the gap between first-principle models and data-driven methods.

A further key goal is to establish a clear extension pathway toward proprietary digital twins. In follow-up projects, industrial partners will be able to integrate their own process data through secure interfaces and to train plant-specific AI models that can predict particle size distributions and performance in real time. In this way, each company will be able to develop customized digital twins that reflect its unique operating conditions while maintaining full data confidentiality.

Finally, the project will provide comprehensive documentation and training materials for IFPRI members. These resources will include theoretical background, use cases, and reproducible examples designed to ensure accessibility and facilitate adoption of the platform across a wide range of industrial users. Through these objectives, the project will not only create a scientifically robust and openly available platform but will also define a practical pathway for industry partners to adapt the technology in subsequent projects to their own processes, thereby maximizing both academic impact and industrial relevance.

### 2.1 Project Scope

The platform will primarily address fine comminution unit operations, with a particular emphasis on stirred media mills, ball mills, and selected configurations of integrated mill–classifier circuits. Its structure will comprise the following main components:

- Model Library: Implementations of validated mechanistic and empirical models.
- Simulation & Dashboard Interface: A user-friendly environment for simulations, parameter studies, and live data visualization.
- Hybrid AI Layer: Proof-of-concept module showing how physics-informed learning enhances model utility.
- Open Data Interfaces: CSV/SQL/OPC-UA connectivity for future industrial integration.

### 2.2 Scope Boundaries

The project will not develop full-scale, company-specific predictive models, but it will conclude with a Partners Incorporation Phase at the end of Phase 1, the three-year IFPRI project. In this phase, selected industrial partners can contribute and analyse their own process data to test and validate the platform in a proof-of-concept setting. Phase 1 therefore delivers the open, shared foundation and demonstrates its applicability in practice. A possible Phase 2, carried out in separately funded follow-up projects, will build on the lessons learned from Phase 1 and

support further development of the platform, including extended implementations and model adaptations with additional industrial partners. This ensures a clear and scalable pathway from an open, pre-competitive basis toward plant-specific digital twins and advanced applications.

### 3. CORE MODELING FRAMEWORK AND INDUSTRIAL RELEVANCE

The proposed platform integrates theoretical models, data connectivity, and visualization in a modular architecture (Figure 2). It serves as educational/operational decision-support environment for process engineers. Figure 3 illustrates one possible exemplary implementation of this concept, showing a dashboard of the open-source platform with digital-twin configuration, real-time metrics, and an interactive PSD visualization.

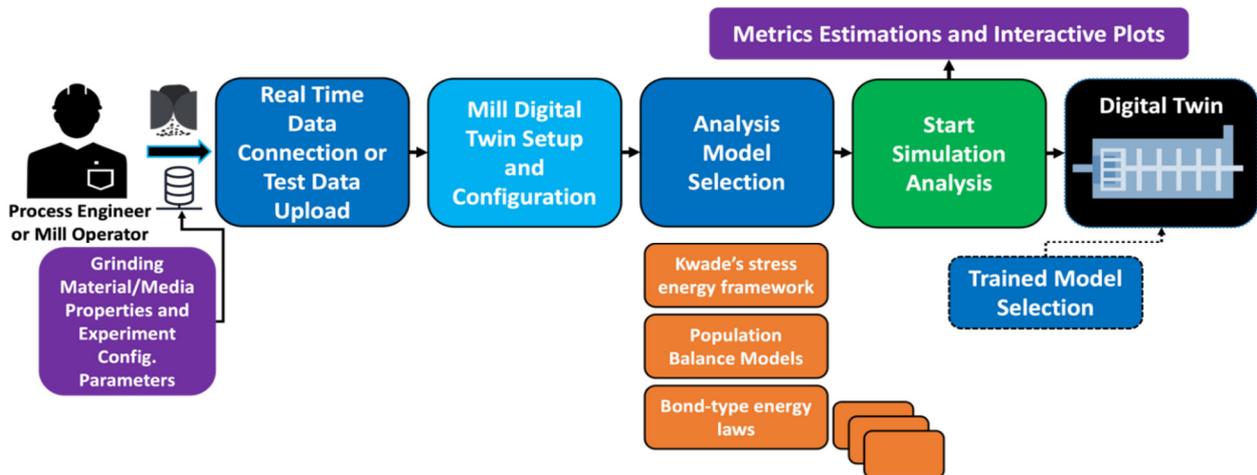


Figure 2: Modular architecture of the Hybrid AI Comminution Platform: from data connection and model selection to simulation, digital-twin integration, and estimation of disperse properties (e.g., PSD, surface area, etc.)

#### 3.1 Workflow Overview

1. Define material and process use cases in close collaboration with industry partners and draw on representative plant data as well as experimental datasets from IPAT (e.g., from previous IFPRI projects or wet-grinding trials) to ensure the platform addresses relevant challenges.
2. Connect to real-time data or upload test datasets.
3. Configure a virtual mill (digital twin setup).
4. Select models (Kwade, Tavares, Bond).
5. Run simulations and analyze results via interactive plots.
6. Optionally, integrate company-specific trained ML models.

#### 3.2 Industrial Use Cases

1. Identify and define relevant industrial use cases together with participating partners to ensure alignment with practical challenges and real plant requirements.
2. Operational Benchmarking: Compare measured mill power and product fineness against model predictions to quantify efficiency losses.
3. Process Troubleshooting: Diagnose deviations (e.g., PSD broadening, unexpected energy spikes) by contrasting data with model responses.
4. Optimization Scenarios: Virtually test the effect of varying stirrer speed, bead size, or slurry viscosity before implementing changes.
5. Training and Knowledge Sharing: Use as an educational platform to train engineers on mechanistic principles and data interpretation.
6. Predictive Digital Twins: For partners providing plant data, integrate custom trained ML models for real-time prediction of PSD and energy use.

### 3.3 Expected Impact

- Improved energy efficiency via quantitative stress and energy mapping.
- Reduced downtime through model-based diagnostics.
- Higher product quality consistency by maintaining PSD targets.
- Faster process development using modelling before physical trials.
- Accessible AI adoption through open documentation and transparent workflows.

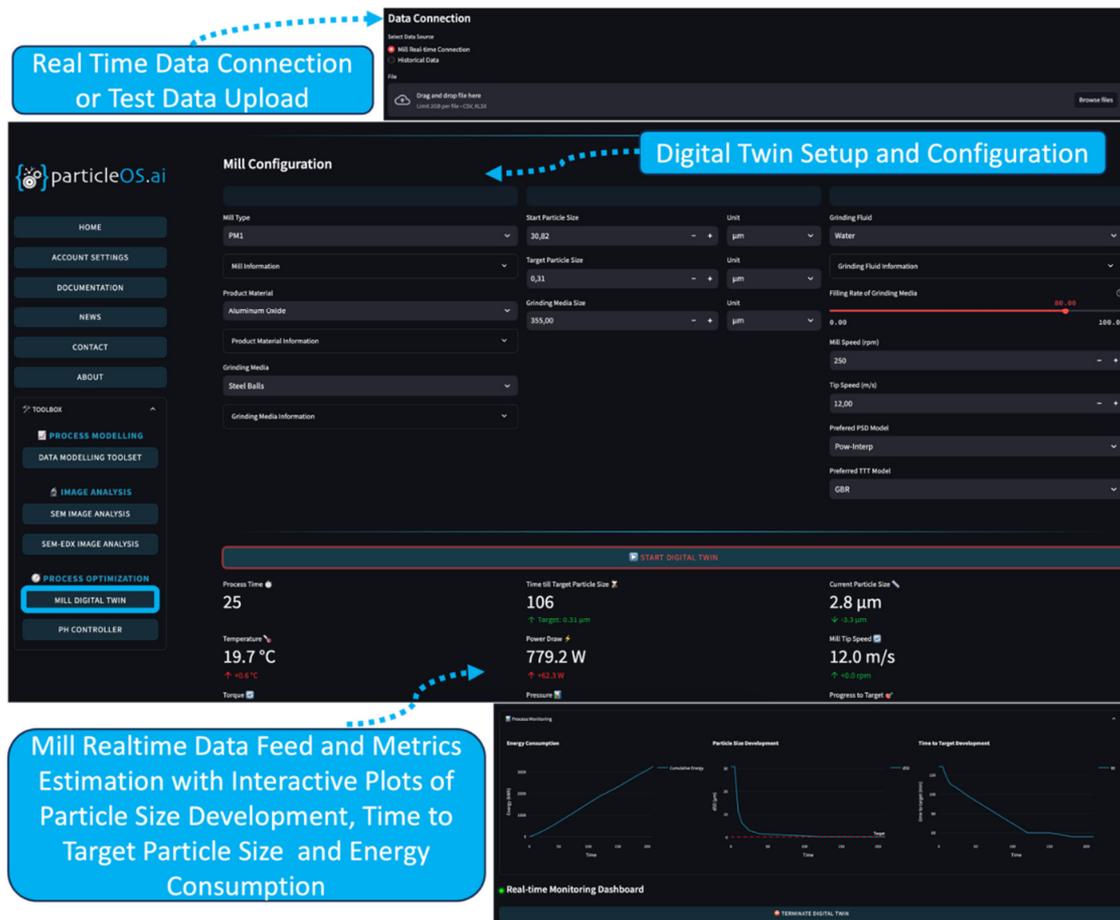


Figure 3: Example dashboard of the open-source platform showing digital-twin configuration, real-time metrics, and interactive PSD visualization.

## 4. WORK PLAN AND DELIVERABLES

Year	Milestones	Key Deliverables
Year 1 – Foundations	Requirements definition, model implementation, prototype dashboard.	Model library (Kwade, PBM, Bond), basic UI, synthetic data simulations.
Year 2 – Integration & Calibration	Connect sample industrial datasets, add AI module, user testing.	Live dashboard, ML-aided calibration routines, documentation draft.

Year	Milestones	Key Deliverables
Year 3 – Validation & Dissemination	Final open-source release, conduct the partners incorporation phase: implement a proof-of-concept with selected industrial partners using their own data, industrial workshops, IFPRI dissemination.	Platform v1.0 (public GitHub), training material, capstone report.
Phase 2	Phase 2 will focus on extending the platform based on the lessons learned during the partners incorporation phase, integrating additional industrial partners, and expanding the framework to cover further comminution and related process operations.	

## 5. COLLABORATION AND DATA STRATEGY

- Engage interested IFPRI members early for feedback on model priorities and user requirements.
- Use open and anonymized datasets for development; no confidential data required in Phase 1.
- Provide secure API interfaces for companies wishing to link plant data privately in Phase 2.
- All open-source code and documentation released under a permissive license (MIT or Apache 2.0).

## 6. EXPECTED OUTCOMES AND INDUSTRIAL BENEFITS

- A validated, open-source hybrid AI comminution platform accessible to all IFPRI members.
- Educational impact: transferable workflows for applying hybrid AI in particle processing.
- Industrial impact: faster optimization cycles, better data utilization, and improved product consistency.
- Strategic impact: a collaborative research foundation that accelerates the digital transformation of fine-particle manufacturing.

## 7. FINANCING

The proposed project is budgeted at 42,000 USD per year over a duration of three years, resulting in a total project funding of 126,000 USD.