Control Of SAG Mills And Its Challenges

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My Background

Technical Support Engineer

Operations Management Consultant

Manager, Environmental Permitting & Regulation

Manager, Climate & Energy

Energy Optimization Lead

Independent Consultant

ICI Chemicals & Polymers Ltd.

CELERANT CONSULTING
Operational strategy and implementation

HYDRO

Spectra Energy

ICF INTERNATIONAL

SaskPower

AREVA

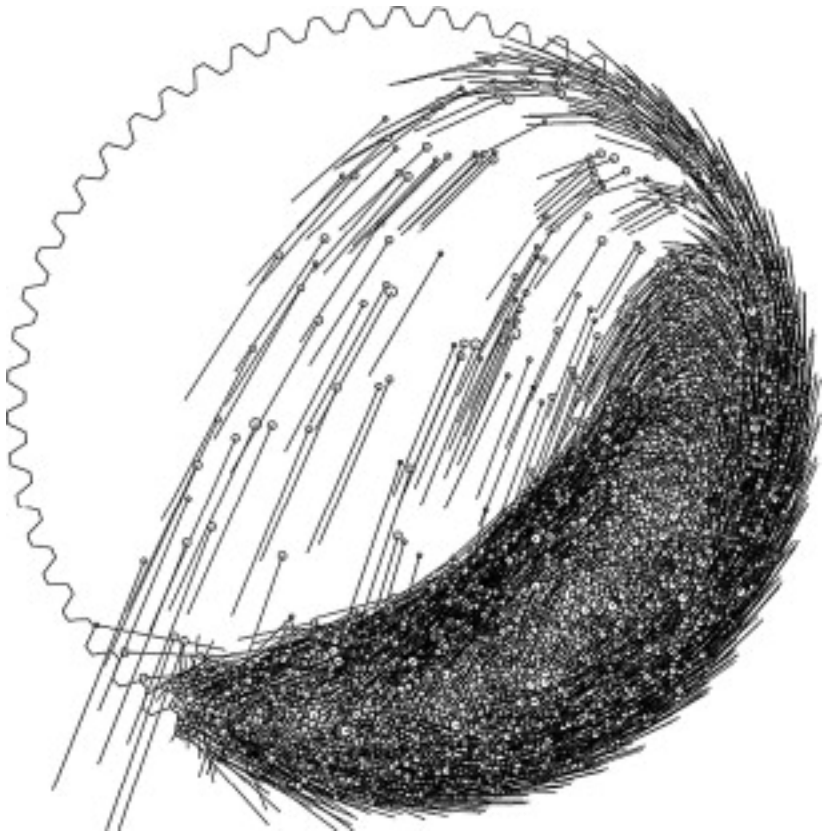
HATCH

Background

SAG Mills Are Used In Large Mining Operations To Grind Crushed Ore Prior To Processing To Recover Valuable Metals

Background

- Grinding occurs inside a rotating drum-shaped mill containing rocks, water, and steel balls
- Size of rock particles is reduced by two processes:
  - *Impact breakage* due to cataracting motion
  - *Attrition* due to cascading motion



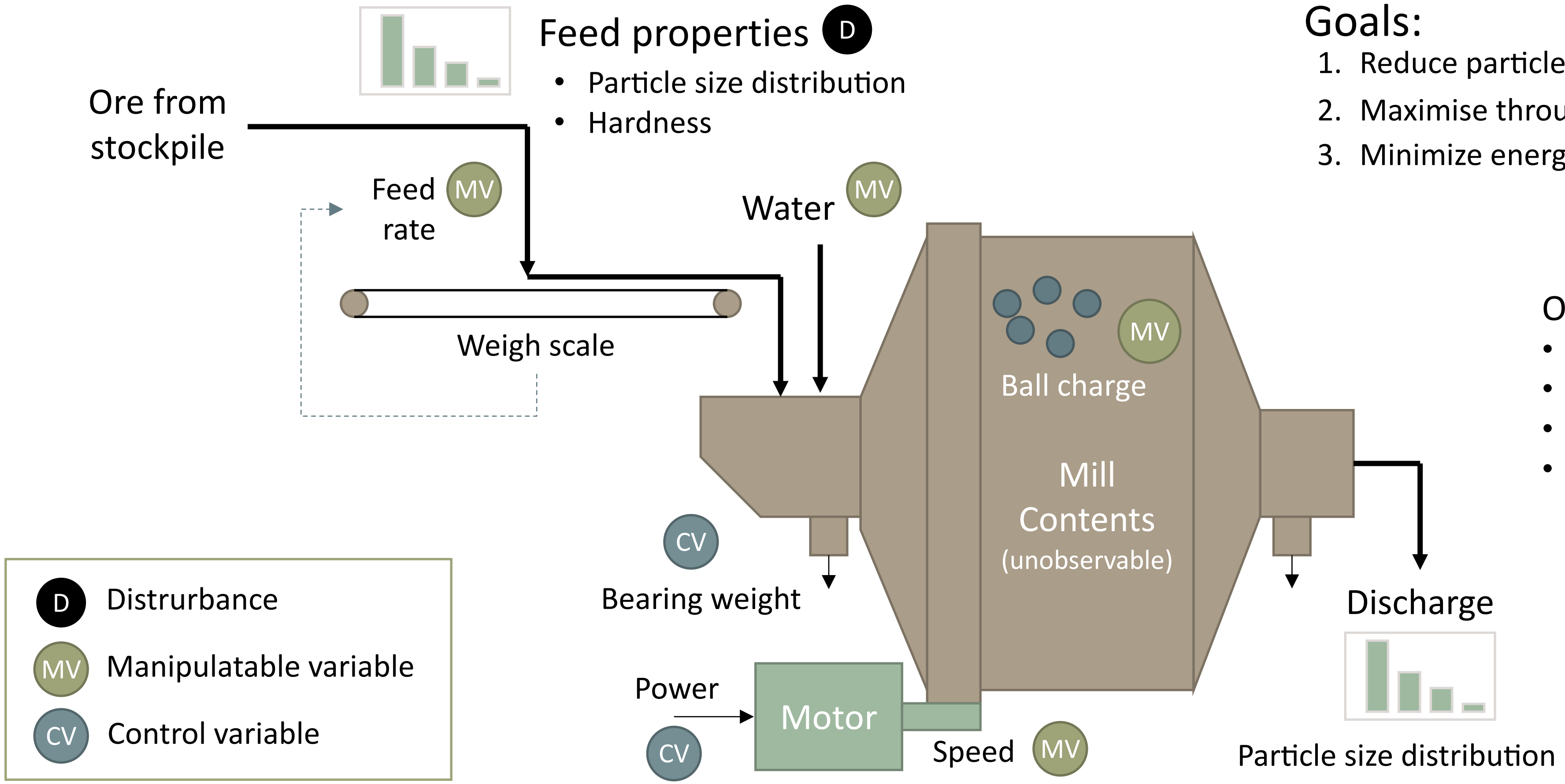
Video simulation: https://vimeo.com/266660541

Source: https://www.sciencedirect.com/science/article/abs/pii/S0892687513002926

SAG Mills Are Used In Large Mining Operations To Grind Crushed Ore Prior To Processing To Recover Valuable Metals

Background

Goals:
1. Reduce particle size
2. Maximise throughput
3. Minimize energy and operating costs.

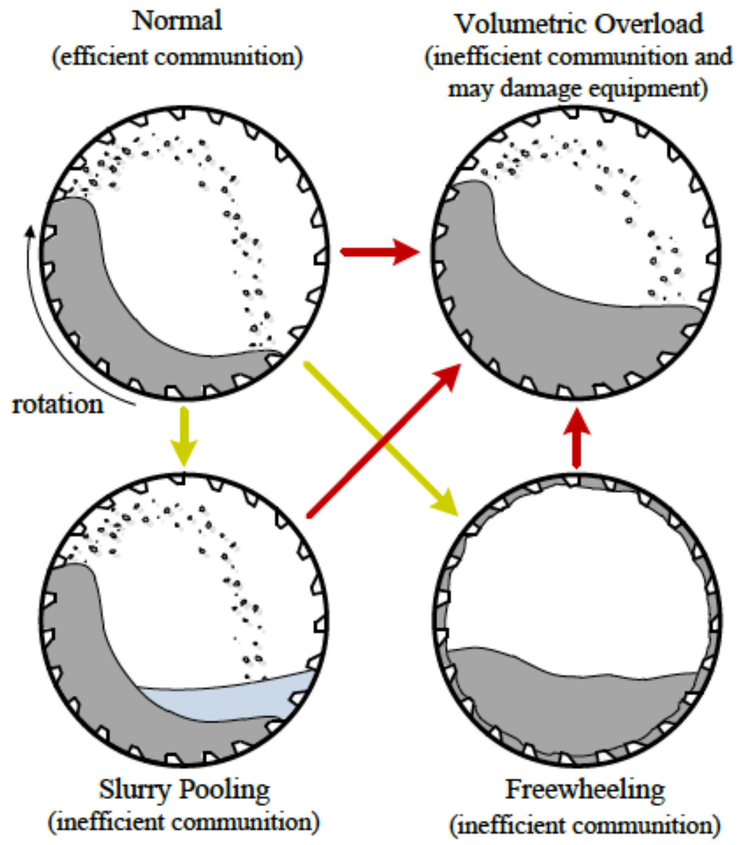


Other types of sensor:
- Vibration
- Acoustic
- Strain gauges
- Accelerometer

Multi-Input, Multi-Output (MIMO) System With Unobservable Internal State

Process Characteristics

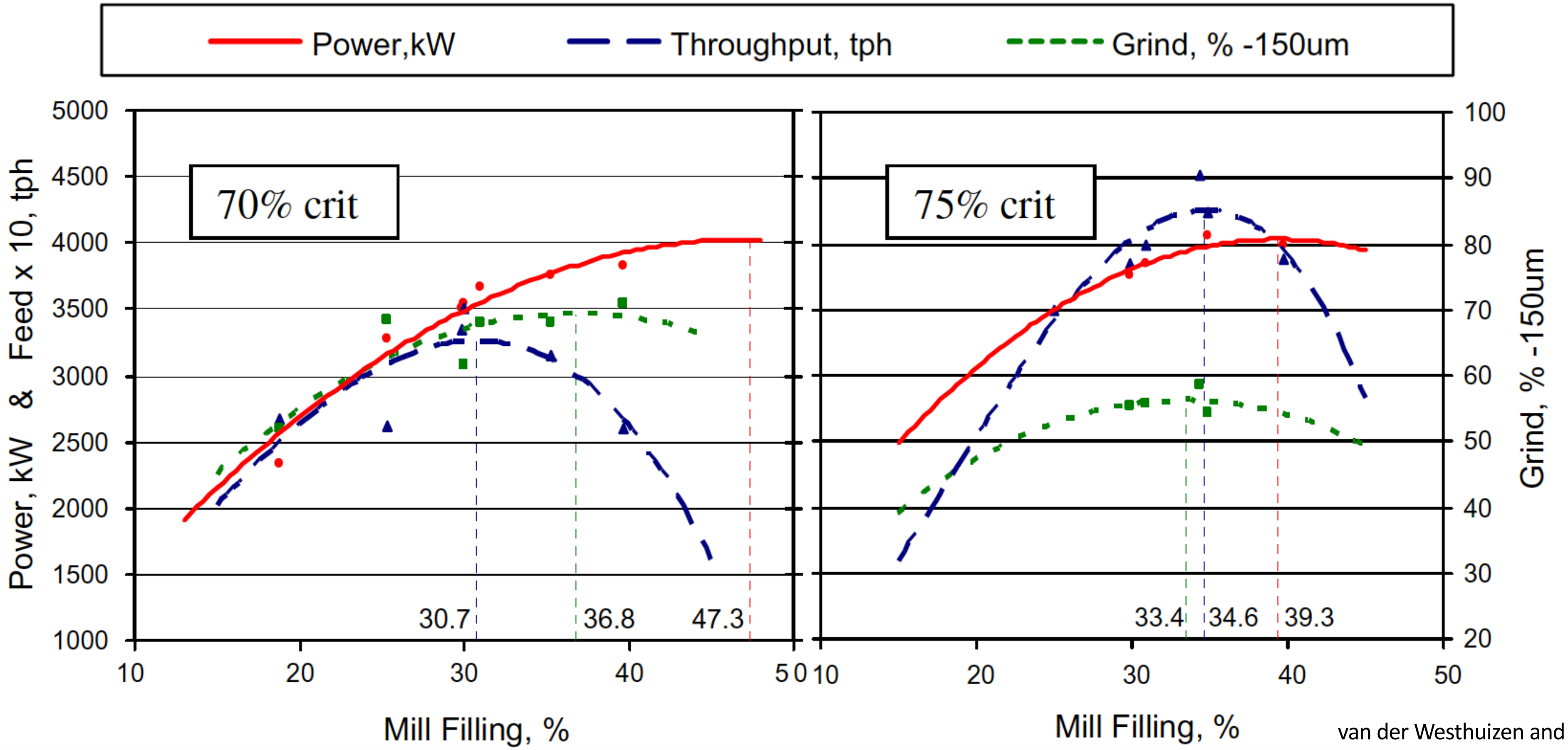
- Control challenges
  - Strong, unobservable disturbances
  - Partially-observable state
  - Non-linear dynamics
  - Circulating load
  - Slow response
  - Noise, measurement error
  - Unstable states
  - Stochastic (rock breakage)
  - Non-stationary (liner and ball wear)
- Probably impossible to build precise model from first principles



Source: McKlure and Gopaluni (2015)

Complex Process With Unstable, Non-Linear Dynamics

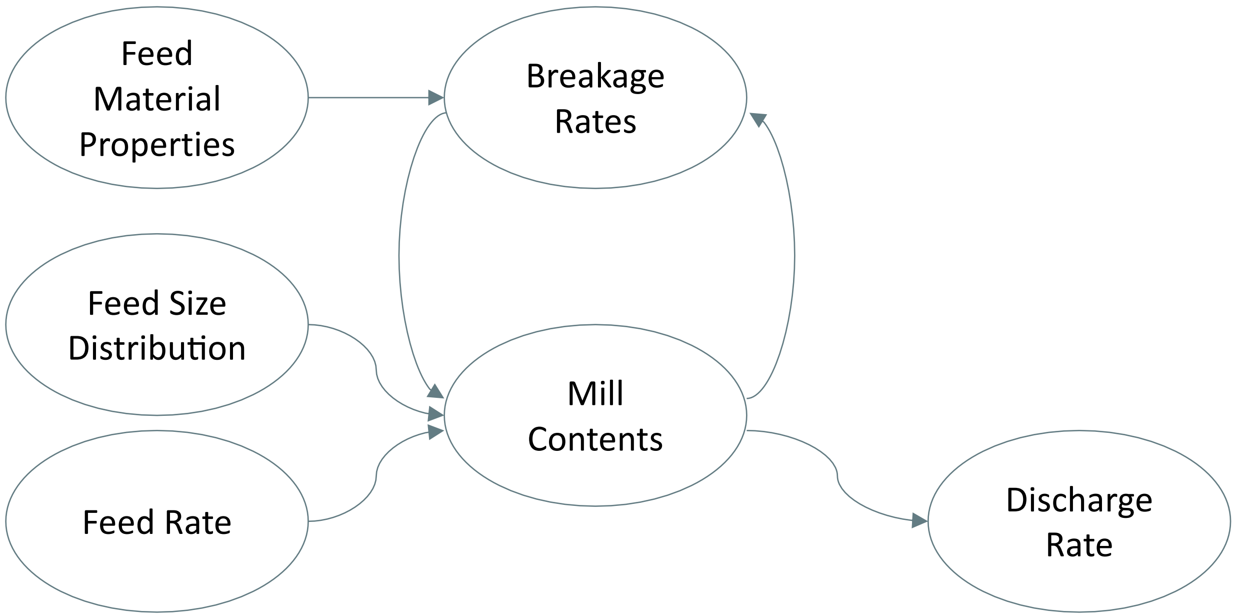
Process Characteristics



van der Westhuizen and Powell (2006)

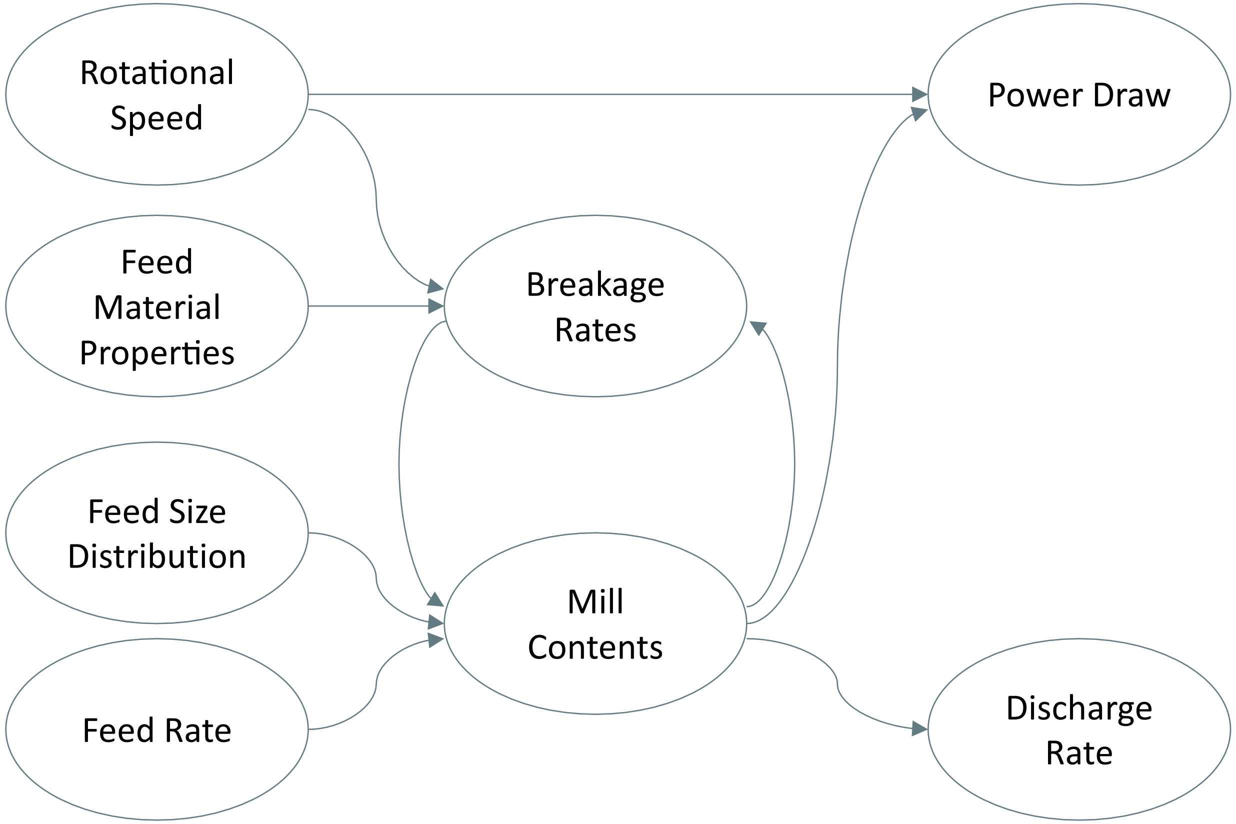
Mill Filling And Speed Have A Significant Effect On Grind, Throughput And Power Consumption

System Dynamics



Interactive Effects Between Mill Contents And Breakage Rates

System Dynamics



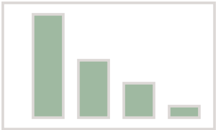
Interactive Effects Between Mill Contents And Breakage Rates

Process Simulation Models

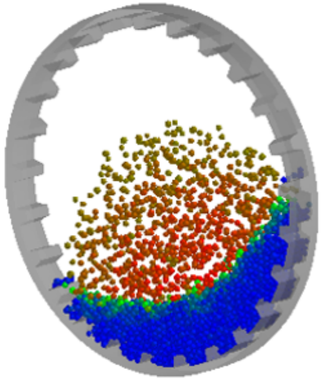
Specific Energy Models → Power Models → Population Balance Models (PBM) → Discrete Element Models (DEM)

Bond Work Index
(kWh/t)

P = f(dimensions,
ore,
speed,
ball size,
rock size)



$$\frac{df_i}{dt} = -S_i f_i + \sum_{j=i-1}^{1} b_{ij} S_j f_j$$



Process Simulation Models Have Evolved From Simple Specific Energy Models To Very Sophisticated DEM Models

Process Simulation Models

Population Balance Model (PBM)

$$p = Df$$

where

$$D = BS + I - S$$

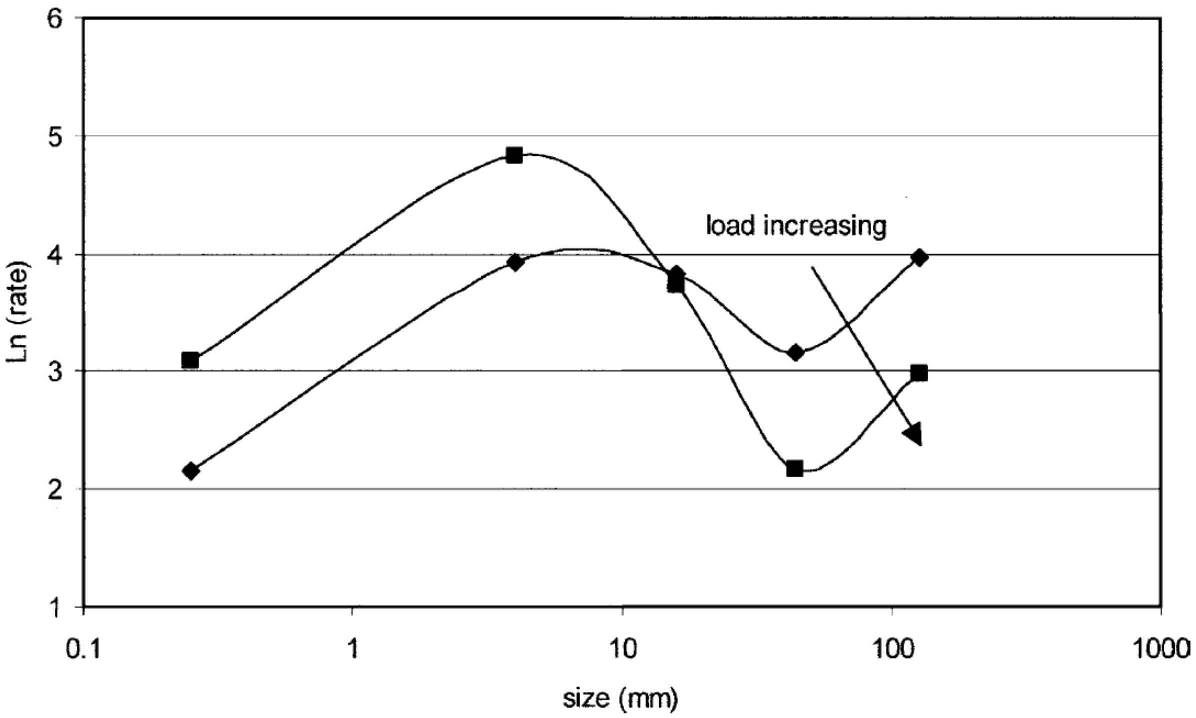
p is the product vector, f the feed vector, B the breakage matrix, I the unit matrix, S the selection matrix; this can be illustrated by considering four size intervals as an example, as follows,

$$\begin{bmatrix} w_i(1) \\ w_2(1) \\ w_3(1) \\ w_4(1) \end{bmatrix} = \begin{bmatrix} b_{11} & 0 & 0 & 0 \\ b_{21} & b_{22} & 0 & 0 \\ b_{31} & b_{32} & b_{33} & 0 \\ b_{41} & b_{42} & b_{43} & b_{44} \end{bmatrix} \begin{bmatrix} s_1 & 0 & 0 & 0 \\ 0 & s_2 & 0 & 0 \\ 0 & 0 & s_3 & 0 \\ 0 & 0 & 0 & s_4 \end{bmatrix} \begin{bmatrix} w_1(0) \\ w_2(0) \\ w_3(0) \\ w_4(0) \end{bmatrix} + \left\{ \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} - \begin{bmatrix} s_1 & 0 & 0 & 0 \\ 0 & s_2 & 0 & 0 \\ 0 & 0 & s_3 & 0 \\ 0 & 0 & 0 & s_4 \end{bmatrix} \right\} \begin{bmatrix} w_1(0) \\ w_2(0) \\ w_3(0) \\ w_4(0) \end{bmatrix}$$

Austin (1971)

The Population Balance Model Is A Linear Matrix Model Based On Breakage Probabilities Of Particles In Discrete Size Intervals

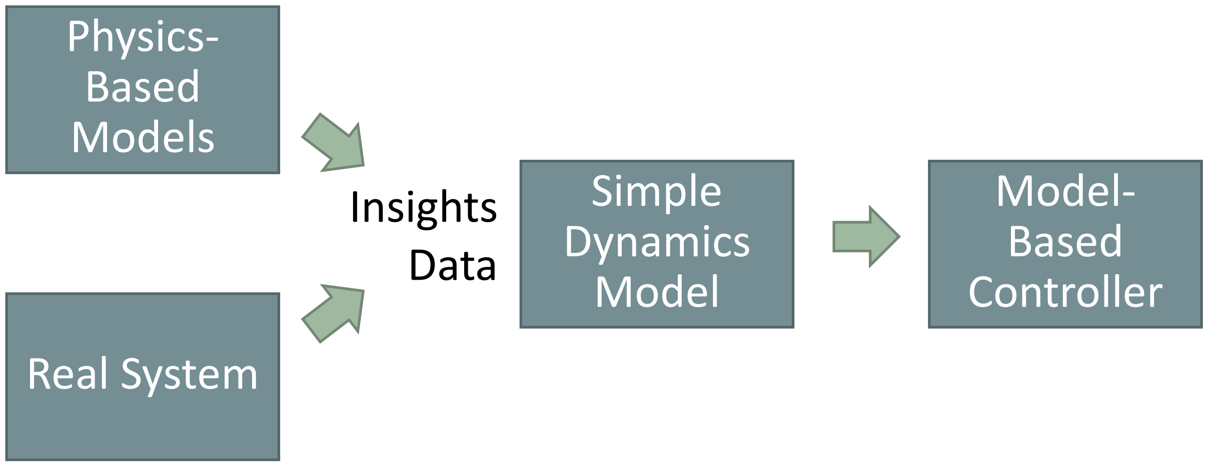
Process Characteristics



Morrell (2004)

It Is Possible To Fit Simple, Parameterized PBM Models To Empirical Data

Our Proposed Approach



Hybrid Data-Driven / Model-Based Approach Utilizing Physics-Based Simulation Models Where Appropriate

Questions, Comments, Ideas…

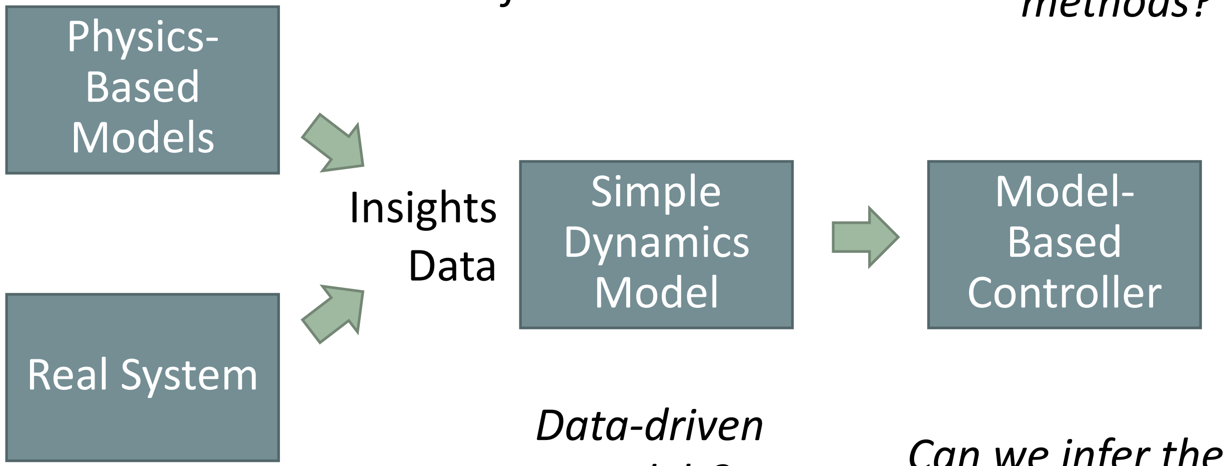
How best to utilize simulation models?

What model form to use?

Applicable control methods?

Non-linear dynamics?

Techniques for system identification?



Constraints?

Data-driven models?

Can we infer the hidden state?

Robustness?

How to explore state-space?

How to deal with sample efficiency?

Model-free methods?

Adaptive control?

Thank You

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References

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- McClure, K. S., & Gopaluni, R. B. (2015). Overload detection in semi-autogenous grinding: A nonlinear process monitoring approach. IFAC-PapersOnLine, 28(8), 960–965. https://doi.org/10.1016/j.ifacol.2015.09.094
- Morrell, S. (2004). A new autogenous and semi-autogenous mill model for scale-up, design and optimisation. Minerals Engineering, 17(3), 437–445. https://doi.org/10.1016/j.mineng.2003.10.013
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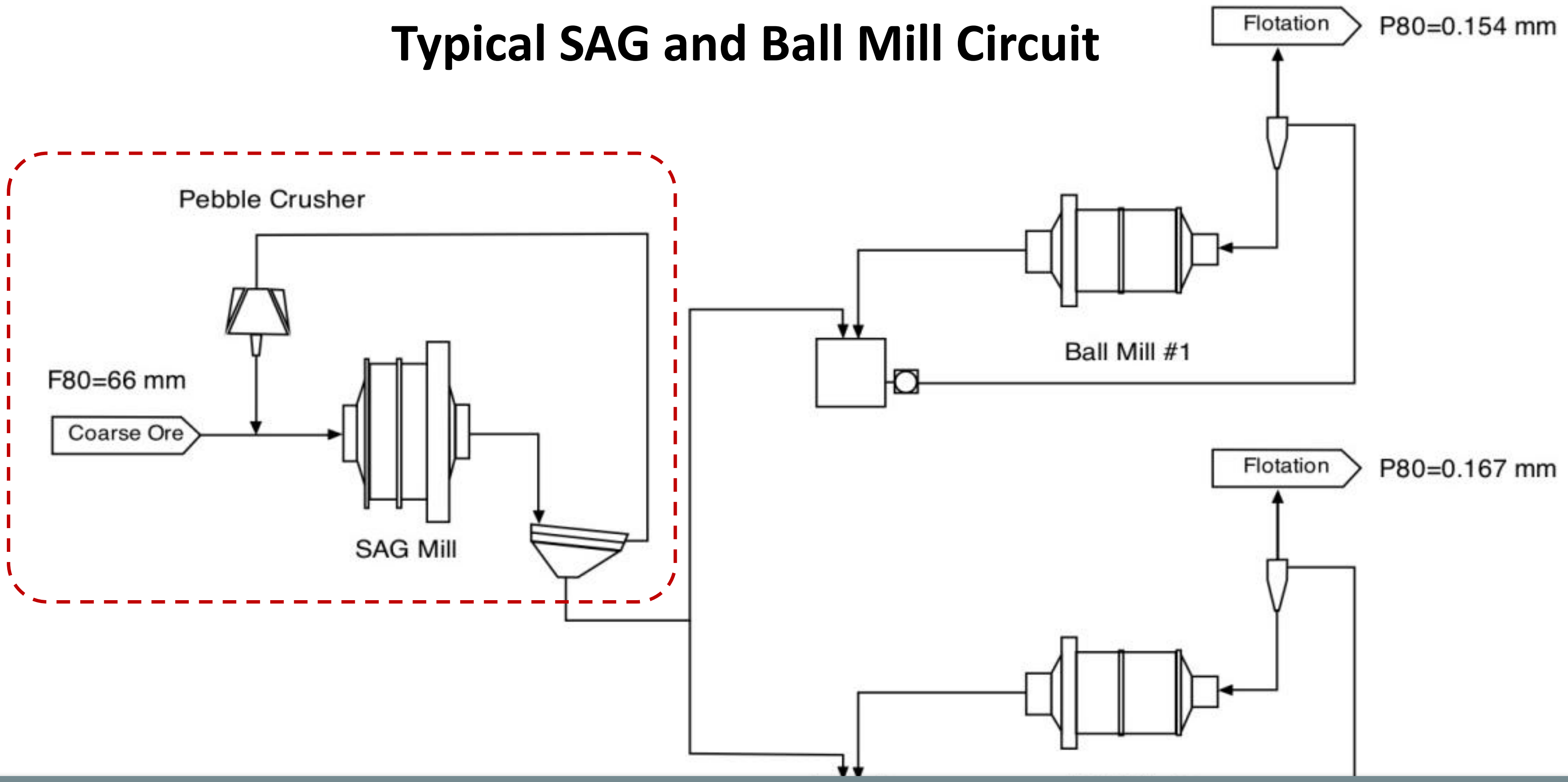
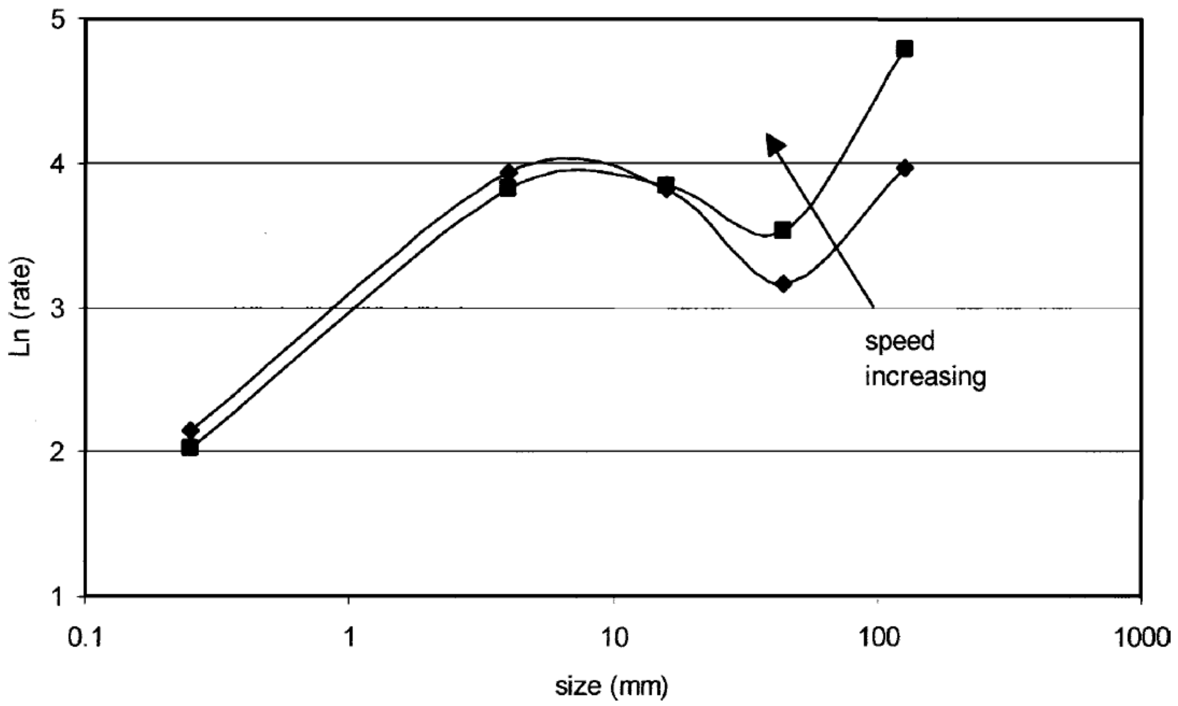
Background

Typical SAG and Ball Mill Circuit



SAG Mill Is The First Stage Of The Grinding Process And Experiences The Most Variability Due To Unobservable Changes In Ore Feed Properties

Process Characteristics



Morrell (2004)

Empirical Work From Pilot-Scale And Full-Scale Mills Provides Some Insights

Good / Relevant Books?

- Multivariable Feedback Control Analysis and Design
  Skogestad & Postlethwaite (2001)
- Practical Grey-box Process Identification
  Bohlin (2006)
- Adaptive Control: 2nd Edition
  Åström & Wittenmar (2008)
- Optimization-Based Control
  Murray (2009)
- Advanced Control and Supervision of Mineral Processing Plants
  Sbárbaro & del Villar (2010)
- Feedback Systems
  Åström & Murray (2011)
- Approximate Dynamic Programming: Solving the Curses of Dimensionality
  Powell (2011)
- Adaptive Control: Algorithms, Analysis and Applications
  Landau, Lozano, M'Saad & Karimi (2011)
- Dynamic Optimization
  Poulsen (2012)
- Dynamic Programming and Optimal Control – Vols I & II
  Bertsekas (2017, 2012)
- Predictive Control for Linear and Hybrid Systems
  Borrelli, Bemporad, & Lucca (2018)
- Reinforcement Learning for Optimal Feedback Control
  Kamalapurkar, Walters, Rosenfeld, & Dixon (2018)
- Linear Stochastic Systems
  Peter Caines (2018)
- Reinforcement Learning And Optimal Control
  Bertsekas (2019)
- Data-Driven Science and Engineering
  Brunton & Kutz (2019)
- Neural Approximations for Optimal Control and Decision
  Zoppoli, Sanguineti, Gnecco, & Parisini (2020)
- Intelligent Optimal Adaptive Control for Mechatronic Systems
  Szuster & Hendzel (2020)