Imperial College London

Advances in the Digitalisation of the Process Industries
IChemE – 20-21 October 2021

Development and validation of a dynamic model for flotation predictive control incorporating froth physics

Paulina Quintanilla *, Stephen Neethling and Pablo Brito-Parada

Advanced Mineral Processing Research Group **

Department of Earth Science and Engineering, Imperial College London

* p.quintanilla18@imperial.ac.uk

** @AMPRG_IMPERIAL

Imperial College London

Advances in the Digitalisation of the Process Industries
IChemE – 20-21 October 2021

Part 1

Development and validation of a dynamic model for flotation predictive control incorporating froth physics

Paulina Quintanilla *, Stephen Neethling and Pablo Brito-Parada

Advanced Mineral Processing Research Group **

Department of Earth Science and Engineering, Imperial College London

* p.quintanilla18@imperial.ac.uk

** @AMPRG_IMPERIAL

Imperial College London

Advances in the Digitalisation of the Process Industries
IChemE – 20-21 October 2021

Part 2

Development and validation of a dynamic model for flotation predictive control incorporating froth physics

Paulina Quintanilla *, Stephen Neethling and Pablo Brito-Parada

Advanced Mineral Processing Research Group **

Department of Earth Science and Engineering, Imperial College London

* p.quintanilla18@imperial.ac.uk

** @AMPRG_IMPERIAL

Imperial College London

Advances in the Digitalisation of the Process Industries
IChemE – 20-21 October 2021

Part 3

Development and validation of a dynamic model for flotation predictive control incorporating froth physics

Paulina Quintanilla *, Stephen Neethling and Pablo Brito-Parada

Advanced Mineral Processing Research Group **

Department of Earth Science and Engineering, Imperial College London

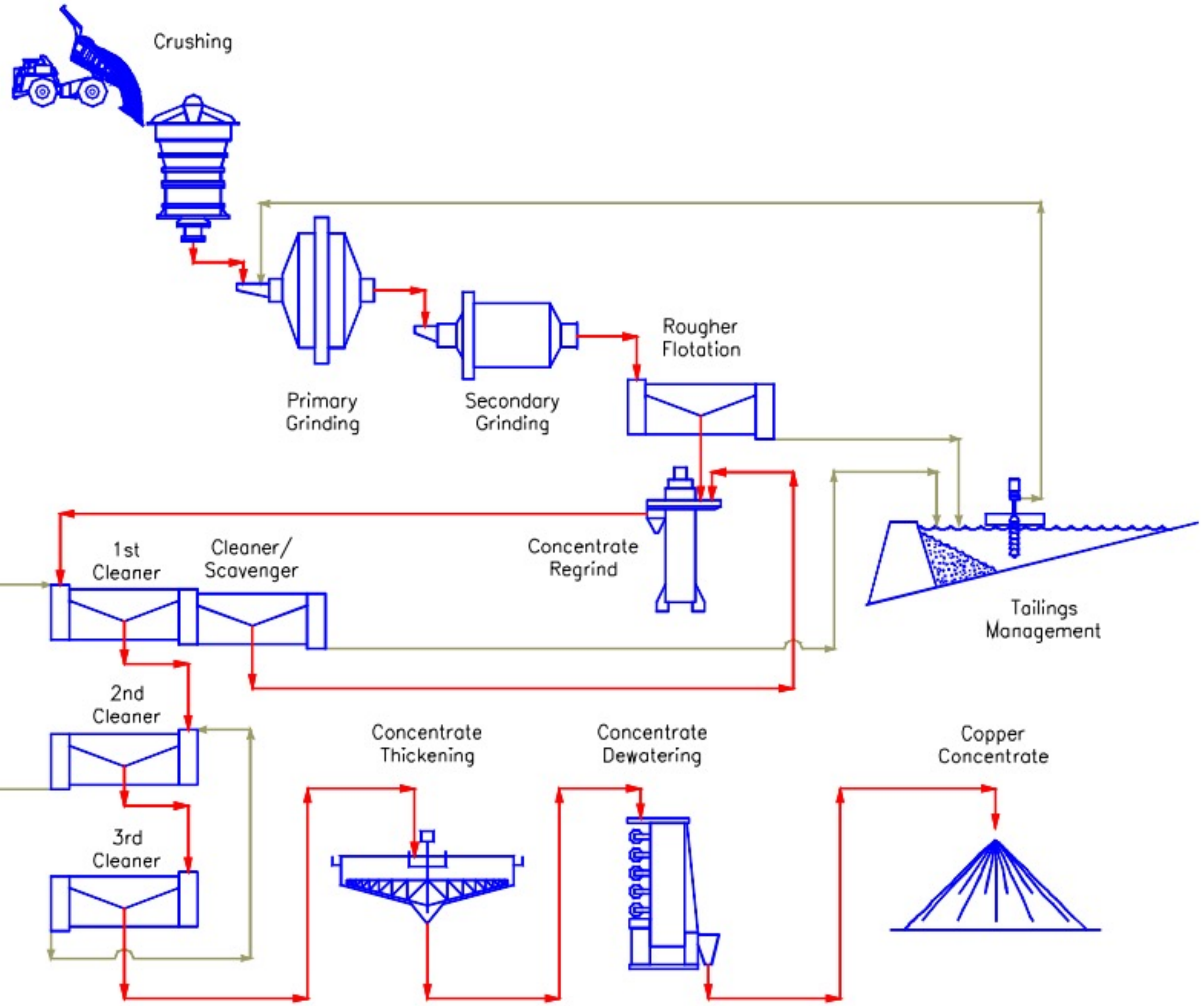
* p.quintanilla18@imperial.ac.uk

** @AMPRG_IMPERIAL

Imperial College London

Mineral processing plant flowsheet

Copper process flowsheet example

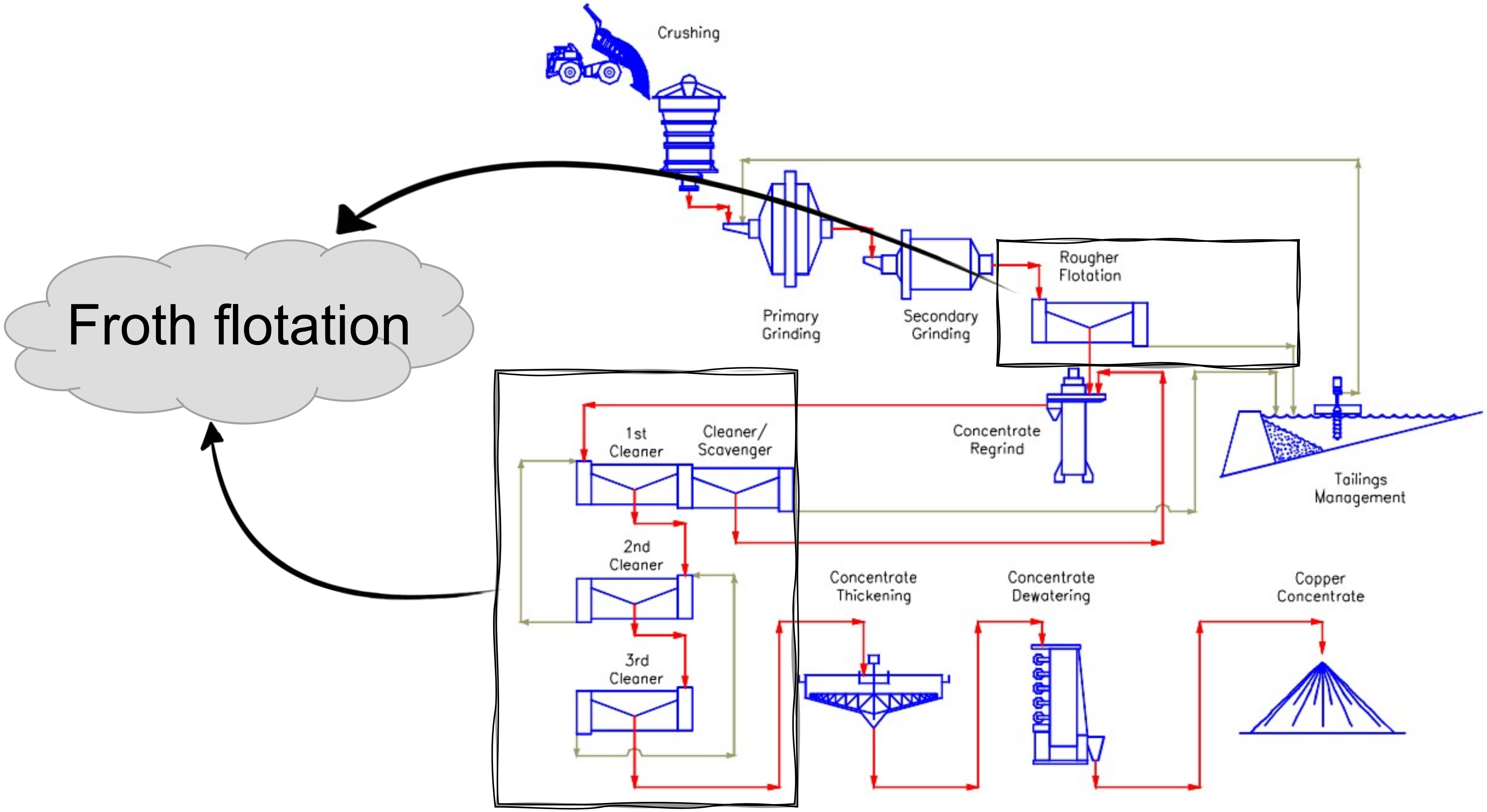


Source: https://www.911metallurgist.com/blog/copper-process-flowsheet-example

Imperial College London

Mineral processing plant flowsheet

Copper process flowsheet example

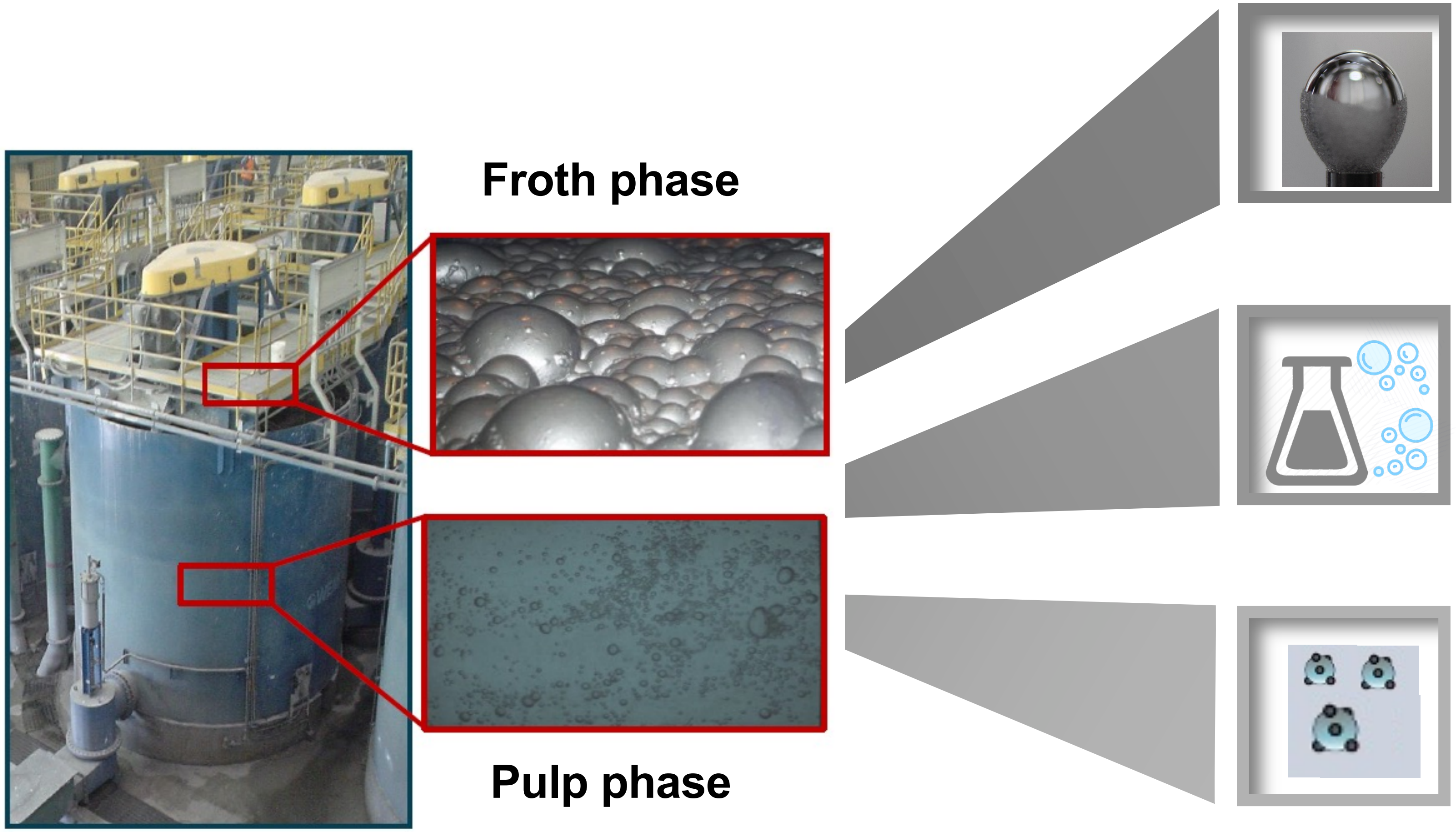


Source: https://www.911metallurgist.com/blog/copper-process-flowsheet-example

Imperial College London

Froth flotation

Recovering valuable minerals through bubbles



Separation of **valuable minerals** from **waste rock** based on **hydrophobicity**.

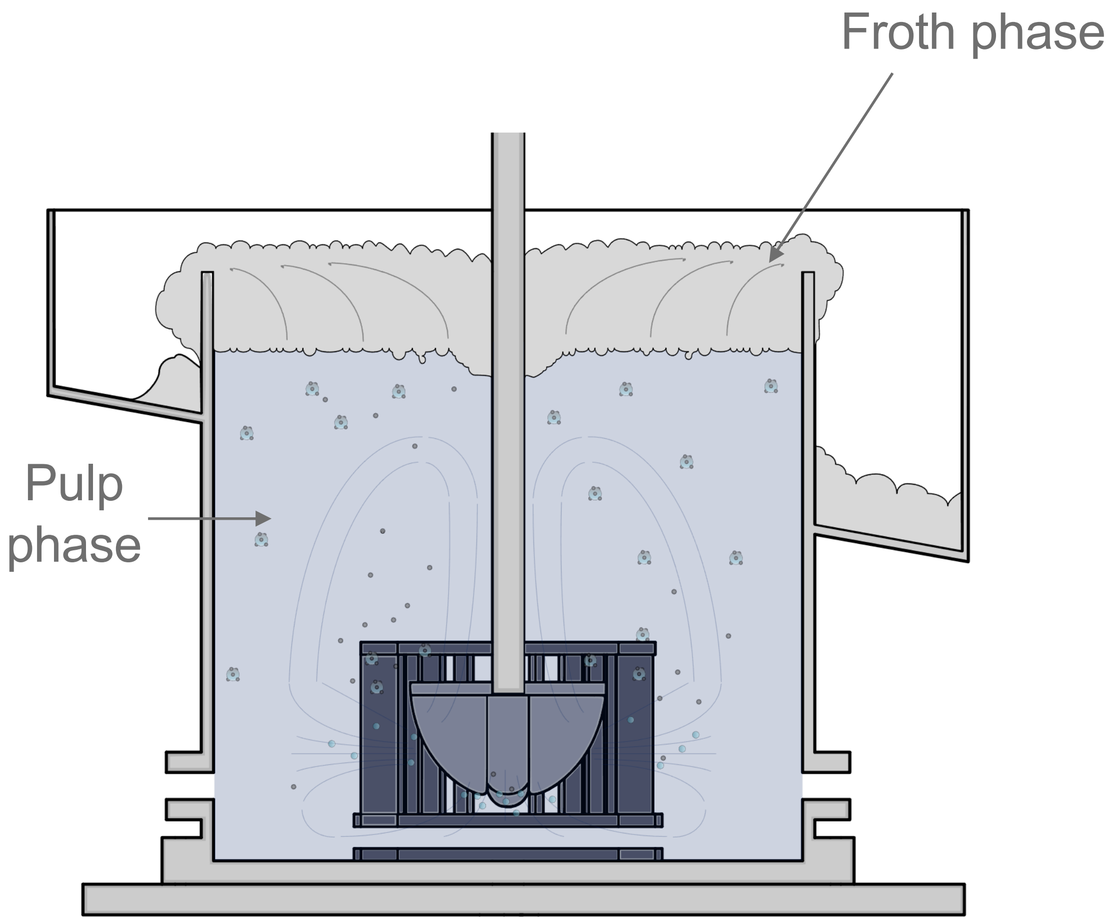
Chemicals and **air** are added into the cell.

Bubble-particles aggregates rise from the **pulp** to the **froth**.

Imperial College London

Froth flotation

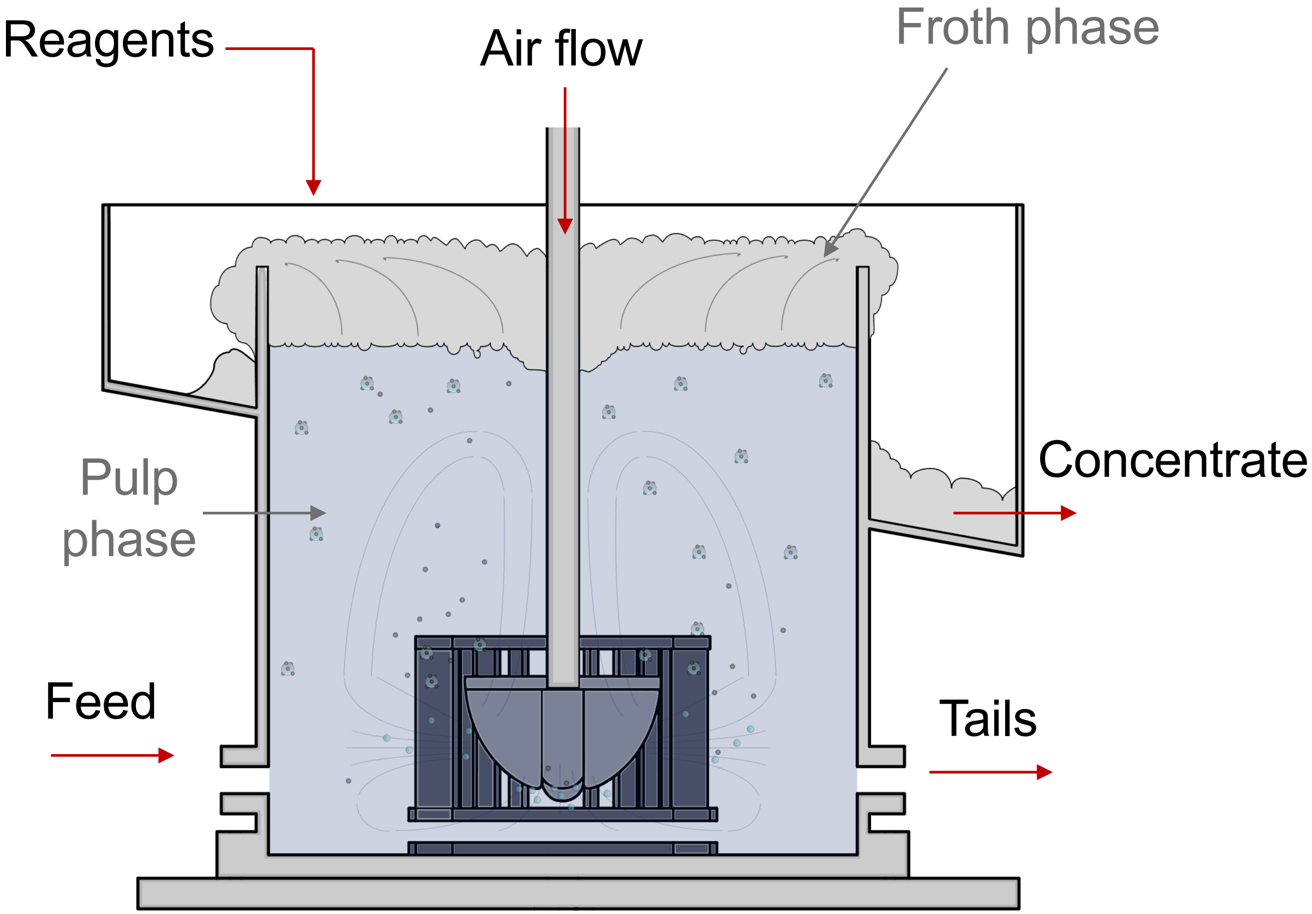
Operating variables



Flotation cell size: 300 m^3

Experimental campaign, Riotinto, Seville, Spain.

Froth flotation
Operating variables



Flotation cell size: 300 m^3

Experimental campaign, Riotinto, Seville, Spain.

Imperial College London

Froth flotation

A large-scale process

Small improvements in its efficiency

Great economic and environmental impacts

How?

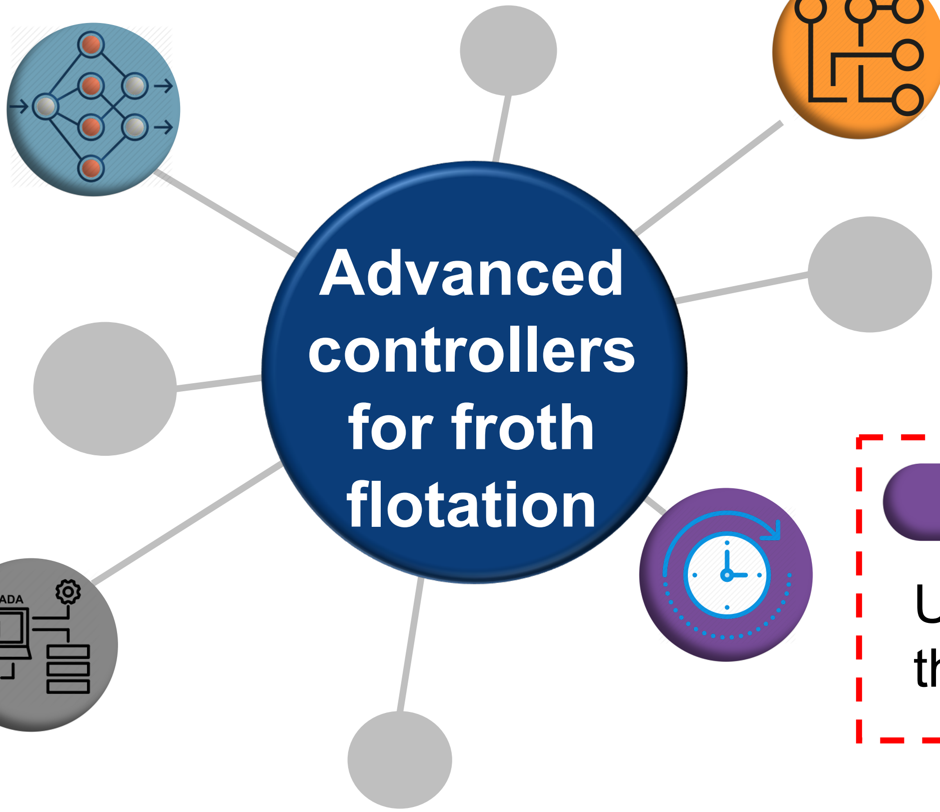
Optimisation by implementing **advanced controller**

Experimental campaign, Riotinto, Seville, Spain.

Imperial College London

Froth flotation

Advanced controllers



Artificial neural

ANN based controller to reach system's setpoints.

Supervisory

Interaction with the **operator.**

Fuzzy logic

Flotation parameters $\in (0, 1)$
IF-THEN rule based strategy.

Model predictive

Use of an **explicit model** of the process.

Imperial College London

Advances in the Digitalisation of the Process Industries
IChemE – 20-21 October 2021

Part 2

Development and validation of a dynamic model for flotation predictive control incorporating froth physics

Paulina Quintanilla *, Stephen Neethling and Pablo Brito-Parada

Advanced Mineral Processing Research Group **

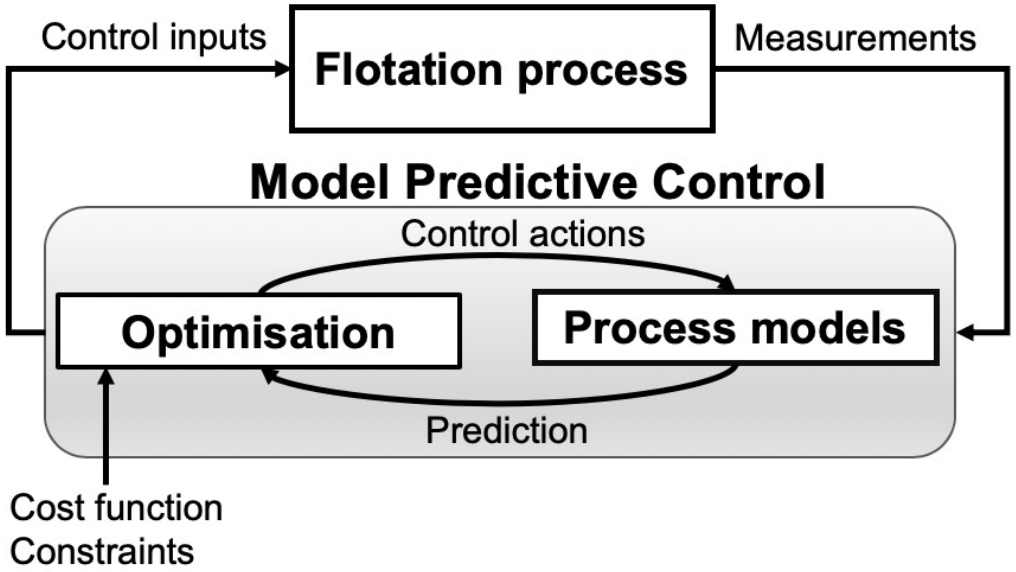
Department of Earth Science and Engineering, Imperial College London

* p.quintanilla18@imperial.ac.uk

** @AMPRG_IMPERIAL

Model Predictive Control

The concept



Use a dynamic model of the process to predict its future evolution and choose the best control action

Optimisation problem

$$min_u J = \int_{t_0}^{t_f} L[x, y, u, w, t] dt$$

s.t. $\frac{dx(t)}{dt} = f(x, y, u, w, t)$

$h(x, y, u, w, t) = 0$

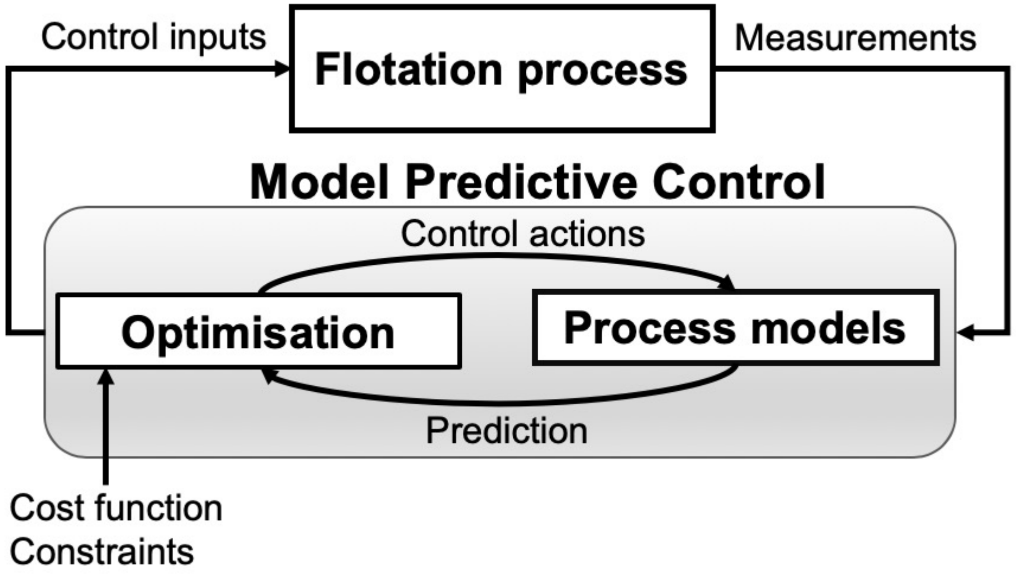
$g(x, y, u, w, t) \leq 0$

$x(t_0) = x_0$ **Feedback!**

Model Predictive Control

The concept

Imperial College London



Optimisation problem

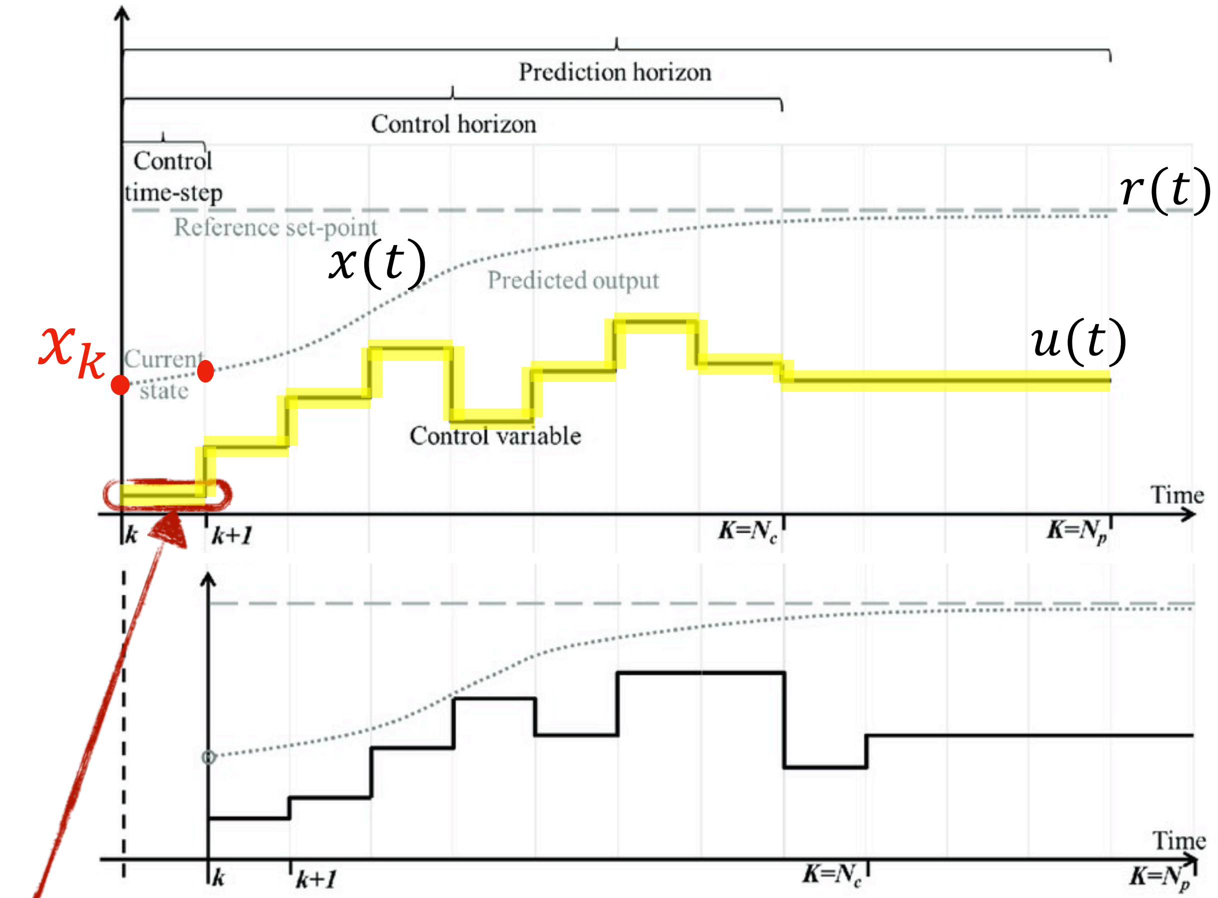
$$\min_u J = \int_{t_0}^{t_f} L[x, y, u, w, t]dt$$

s.t. $\frac{dx(t)}{dt} = f(x, y, u, w, t)$

$h(x, y, u, w, t) = 0$

$g(x, y, u, w, t) \leq 0$

$x(t_0) = x_0$ **Feedback!**



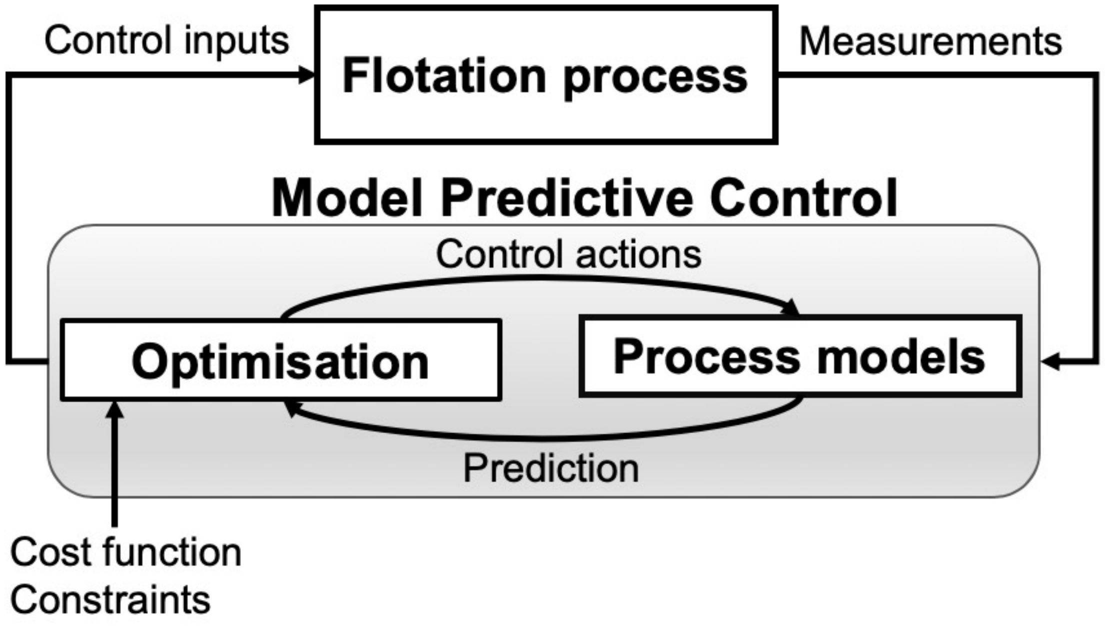
Receding horizon

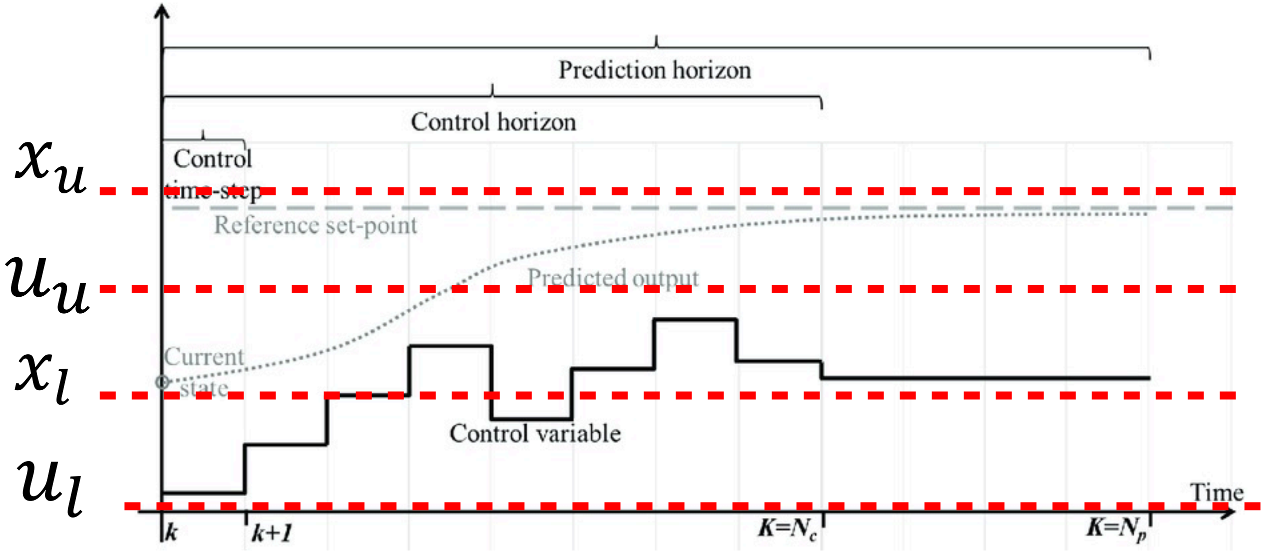
Apply the first optimal move $u(t) = u_0^*$,
throw the rest of the sequence away

At time $t + 1$: obtain new measurements, repeat the optimisation.

Model Predictive Control

Process constraints





- Receding control horizon
- Use of an explicit model of the process
- **Include process constraints**

Model Predictive Control

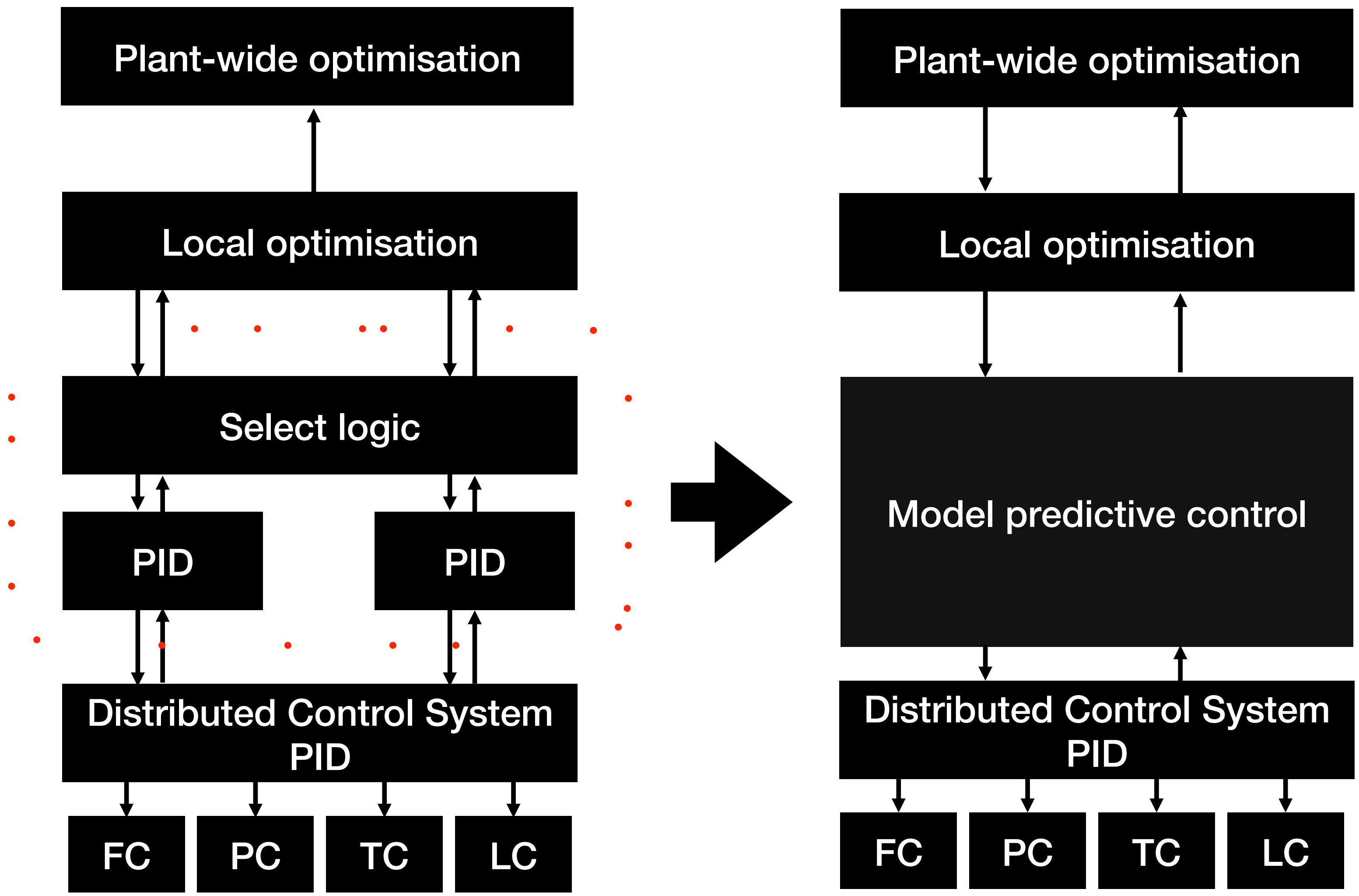
MPC in the operational hierarchy

- Make fine adjustments for local units

- Take each local unit to the optimal condition fast but smoothly without violating the **constraints**

Optimisation layer

- Determine plant-wide the optimal operating condition for the day



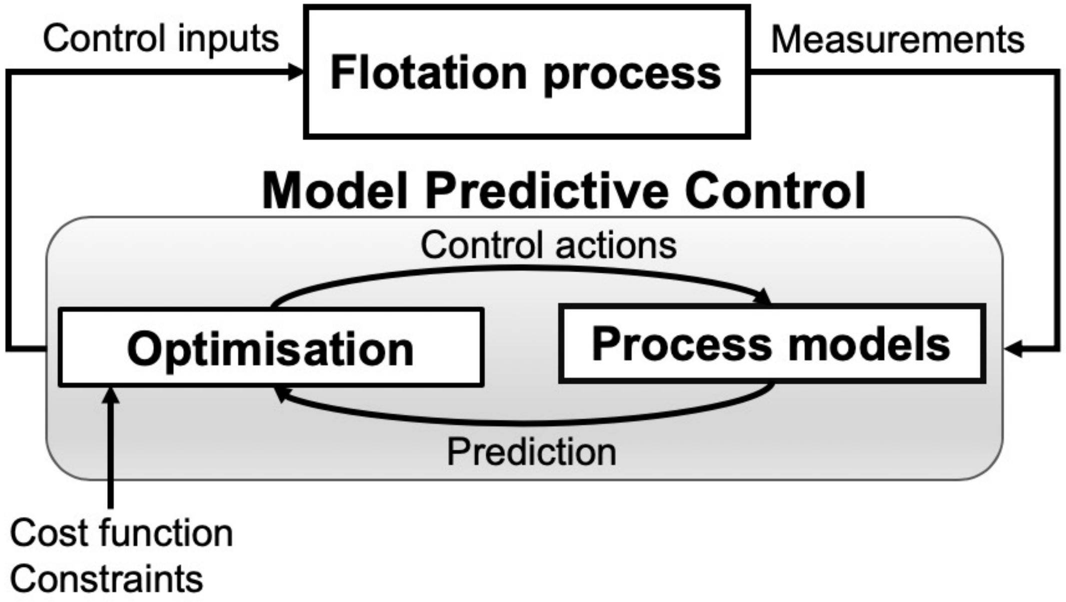
Imperial College London

Model Predictive Control

Why modelling for process control is important?

simplified

Use a dynamic model of the process to predict its future evolution and choose the best control action



Optimisation problem

$$min_u J = \int_{t_0}^{t_f} L[x,y,u,w,t]dt$$

s.t. $\frac{dx(t)}{dt} = f(x,y,u,w,t)$

$$h(x,y,u,w,t) = 0$$

$$g(x,y,u,w,t) \leq 0$$

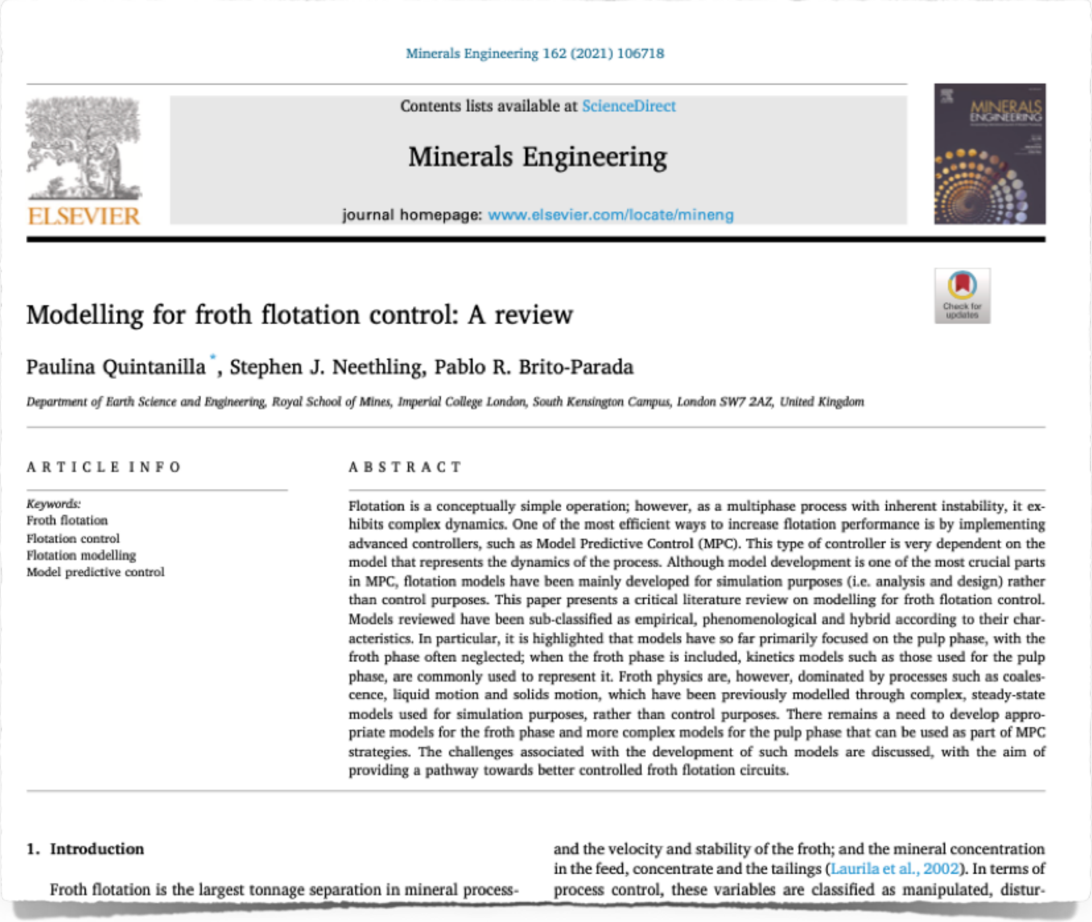
$$x(t_0) = x_0$$

Poor model → Poor prediction → Poor performance

Imperial College London

Modelling for flotation control

State-of-the-art



Minerals Engineering 162 (2021) 106718

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

ELSEVIER

Modelling for froth flotation control: A review

Paulina Quintanilla *, Stephen J. Neethling, Pablo R. Brito-Parada

Department of Earth Science and Engineering, Royal School of Mines, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom

ARTICLE INFO

Keywords:
Froth flotation
Flotation control
Flotation modelling
Model predictive control

ABSTRACT

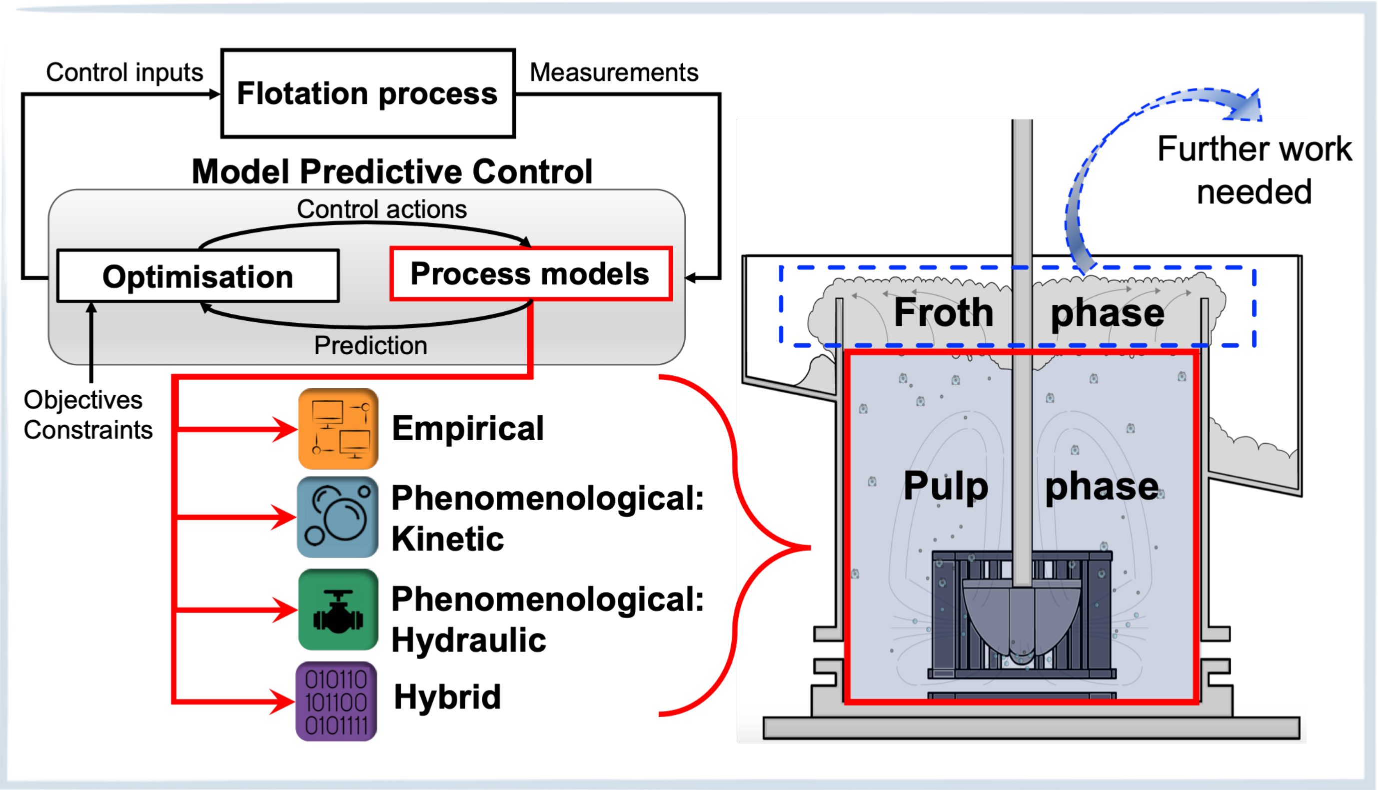
Flotation is a conceptually simple operation; however, as a multiphase process with inherent instability, it exhibits complex dynamics. One of the most efficient ways to increase flotation performance is by implementing advanced controllers, such as Model Predictive Control (MPC). This type of controller is very dependent on the model that represents the dynamics of the process. Although model development is one of the most crucial parts in MPC, flotation models have been mainly developed for simulation purposes (i.e. analysis and design) rather than control purposes. This paper presents a critical literature review on modelling for froth flotation control. Models reviewed have been sub-classified as empirical, phenomenological and hybrid according to their characteristics. In particular, it is highlighted that models have so far primarily focused on the pulp phase, with the froth phase often neglected; when the froth phase is included, kinetics models such as those used for the pulp phase, are commonly used to represent it. Froth physics are, however, dominated by processes such as coalescence, liquid motion and solids motion, which have been previously modelled through complex, steady-state models used for simulation purposes, rather than control purposes. There remains a need to develop appropriate models for the froth phase and more complex models for the pulp phase that can be used as part of MPC strategies. The challenges associated with the development of such models are discussed, with the aim of providing a pathway towards better controlled froth flotation circuits.

1. Introduction

Froth flotation is the largest tonnage separation in mineral process-

and the velocity and stability of the froth; and the mineral concentration in the feed, concentrate and the tailings (Laurila et al., 2002). In terms of process control, these variables are classified as manipulated, distur-

https://doi.org/10.1016/j.mineng.2020.106718



Imperial College London

Advances in the Digitalisation of the Process Industries
IChemE – 20-21 October 2021

Part 3

Development and validation of a dynamic model for flotation predictive control incorporating froth physics

Paulina Quintanilla *, Stephen Neethling and Pablo Brito-Parada

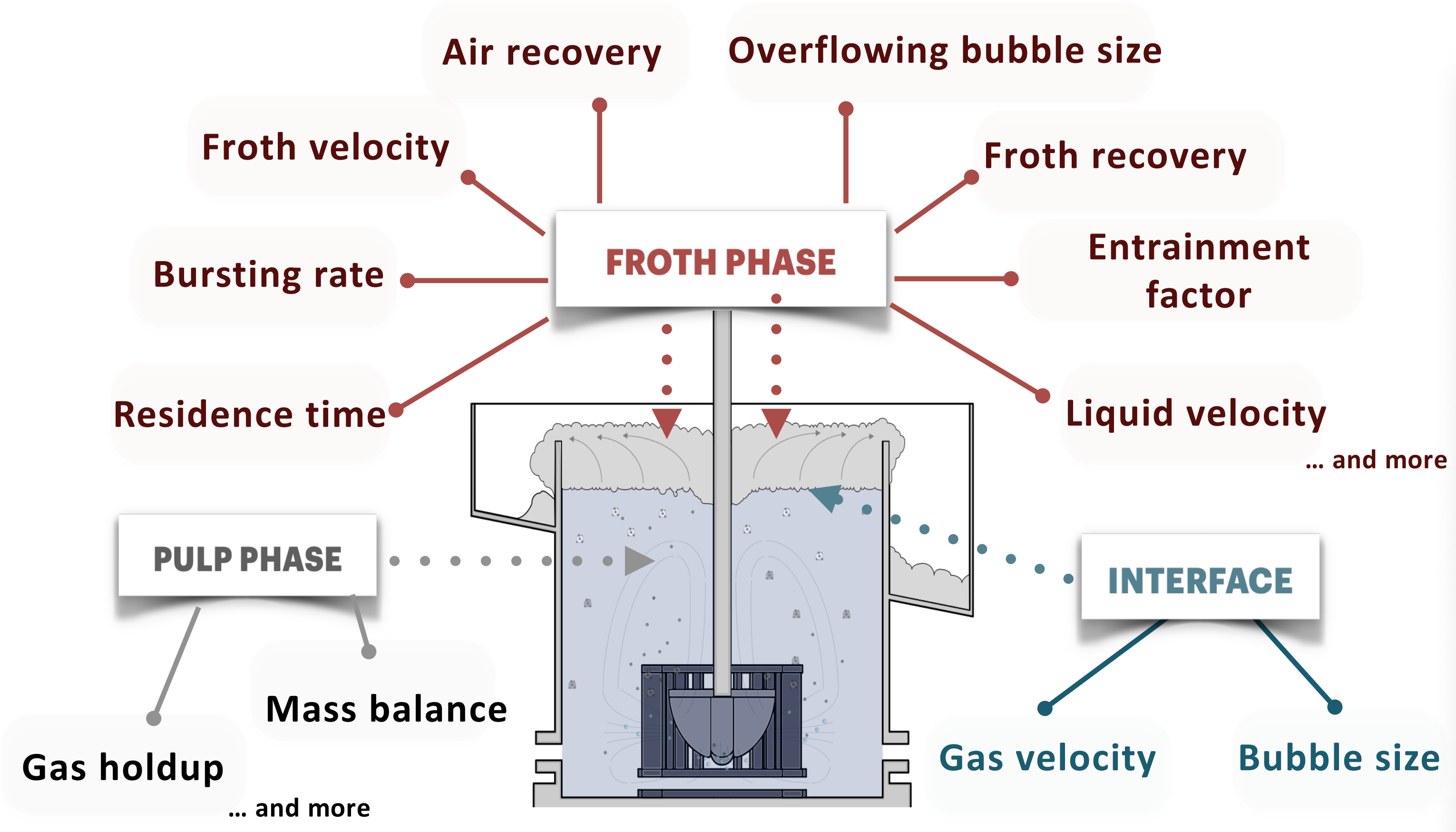
Advanced Mineral Processing Research Group **

Department of Earth Science and Engineering, Imperial College London

* p.quintanilla18@imperial.ac.uk

** @AMPRG_IMPERIAL

Dynamic flotation model



Differential and Algebraic Equations (DAE System)

Minerals Engineering 173 (2021) 107192

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

A dynamic flotation model for predictive control incorporating froth physics. Part I: Model development

Paulina Quintanilla [a,*], Stephen J. Neethling [a], Daniel Navia [b], Pablo R. Brito-Parada [a]

[a] Department of Earth Science and Engineering, Royal School of Mines, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom
[b] Departamento de Ingeniería Química y Ambiental, Universidad Técnica Federico Santa María, Campus San Joaquín, Santiago, Chile

ARTICLE INFO

Keywords:
Froth flotation
Flotation modelling
Flotation control
Flotation simulations
Model predictive control
Sensitivity analysis

ABSTRACT

It is widely accepted that the implementation of model-based predictive controllers (MPC) ensures optimal operation if an accurate model of the process is available. In the case of froth flotation, modelling for control purposes is a challenging task due to inherent process instabilities. Most models for control have only focused on the pulp phase rather than the froth phase, which is usually oversimplified or even neglected. Despite the fact that froth stability can significantly affect the overall performance of flotation cells, there is still a gap in literature regarding flotation models for control purposes that properly include froth physics.

In this paper we describe the development of a dynamic flotation model suitable for model predictive control, incorporating equations that describe the physics of flotation froths. Unlike other flotation models for control in the literature, the model proposed here includes important variables related to froth stability, such as bursting rate and air recovery, as well as simplified equations to calculate froth recovery and entrainment. These model equations allow estimating the amount of valuable material reporting to the concentrate, which can be used as a proxy to estimate grade and recovery. Additionally, pulp-froth interface physics was also included in our model, which enables a more accurate prediction of relevant flotation variables.

A sensitivity analysis of the parameters showed that two out of seven parameters were highly sensitive. The highly sensitive parameters are the exponential factor n of the equation for the overflowing bubble size, and the constant value a of the equation for the bursting rate. Although the other parameters showed a reasonably lower sensitivity than n and a, the results also revealed that there is a significant difference in the prediction accuracy if the parameters are poorly estimated. Further simulations of important variables for control exhibited a good adaptability to changes in typical variables, such as air and feed flowrates.

An analysis of degrees of freedom of the model established that two variables need to be fixed to have a completely determined system. This means that two variables are available for control purposes, which can be air and tailings flowrates (through the manipulation of the respective control valves). This study therefore paves the way for the implementation of a robust dynamic model for flotation predictive control, incorporating important froth phenomena.

1. Introduction

Control and optimisation of the froth flotation process have generated considerable research interest as even small improvements in the separation efficiency translate into important increments in production

remains a challenge as it strongly relies on a dynamic model of the process that accurately predicts the future behaviour of the system (Desbiens et al., 1994, 1998; Bouchard et al., 2009; Sbarbaro and del Villar, 2010; Bergh and Yianatos, 2011; Shean and Cilliers, 2011; Quintanilla et al., 2021).

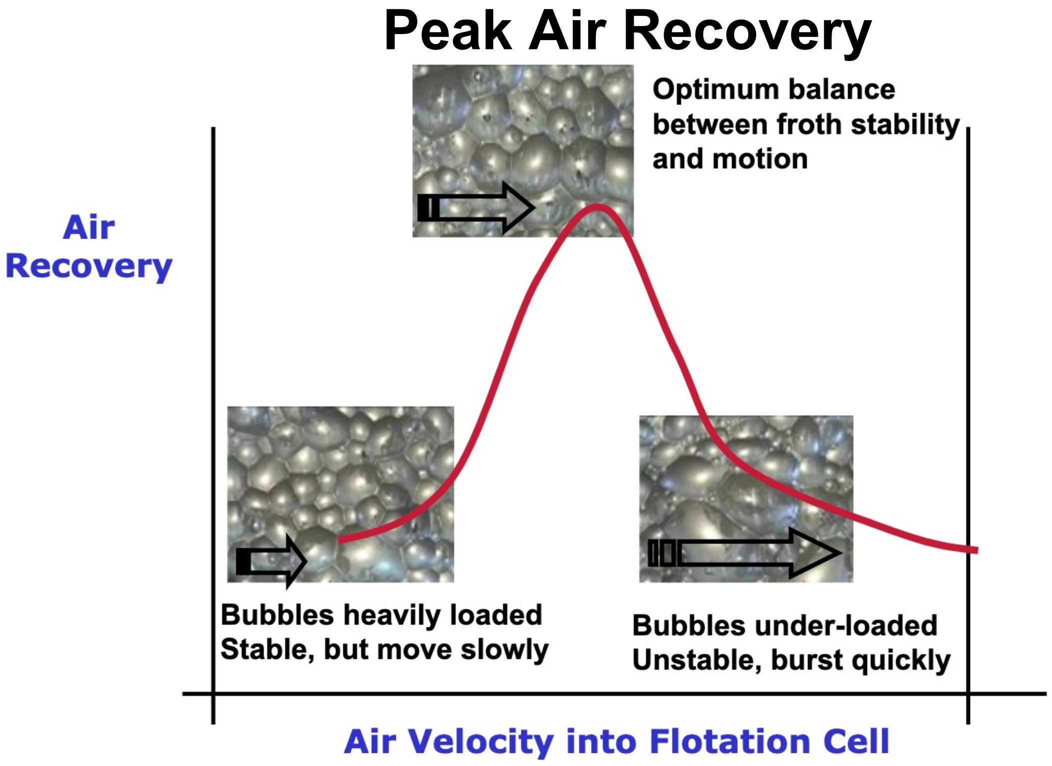
https://doi.org/10.1016/j.mineng.2021.107192

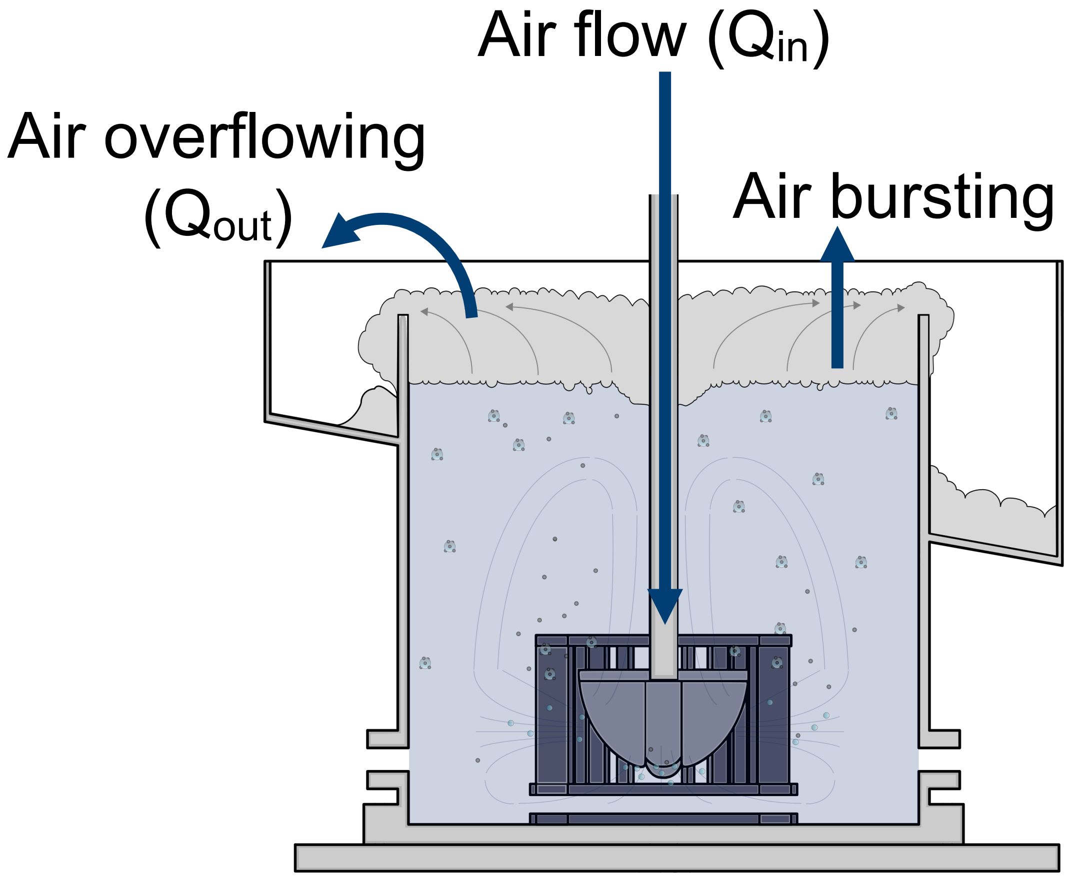
Imperial College London

Dynamic flotation model

Air recovery

$$\textbf{Air recovery:}\ \alpha = \frac{Q_{air,out}}{Q_{air,in}} = \frac{v_f\, L_{lip} h_{froth}}{Q_{air,in}}$$





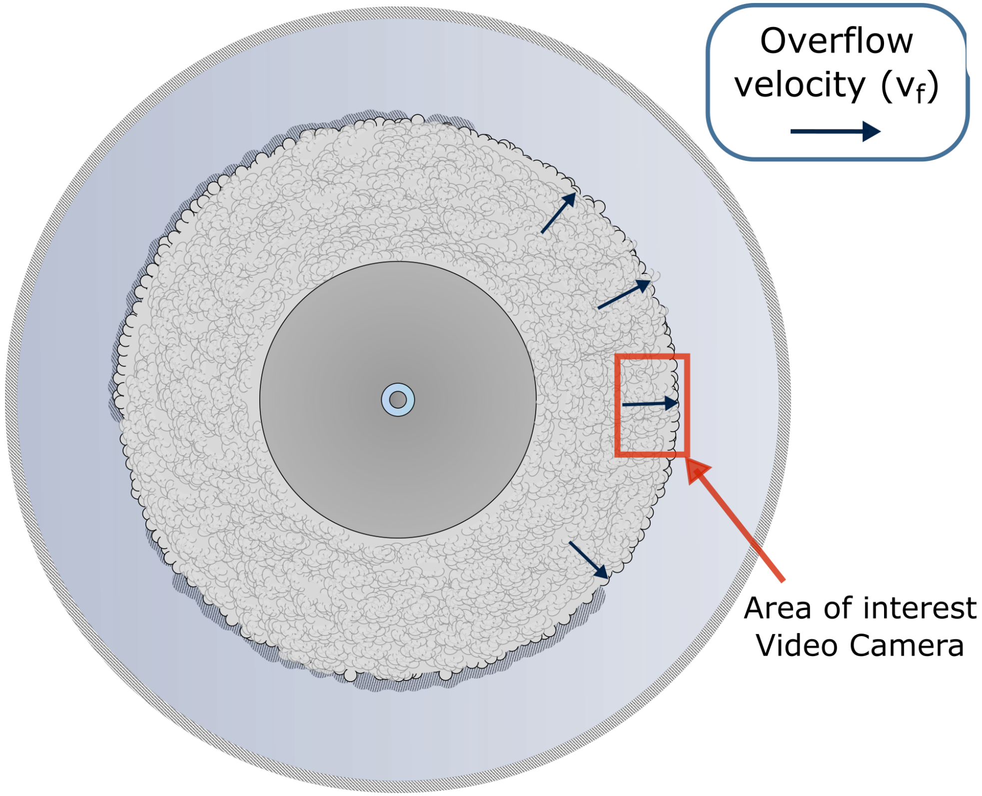
Hadler, K., & Cilliers, J. (2009). **The relationship between the peak in air recovery and flotation bank performance.** Minerals Engineering, 22(5), 451–455. https://doi.org/10.1016/j.mineng.2008.12.004

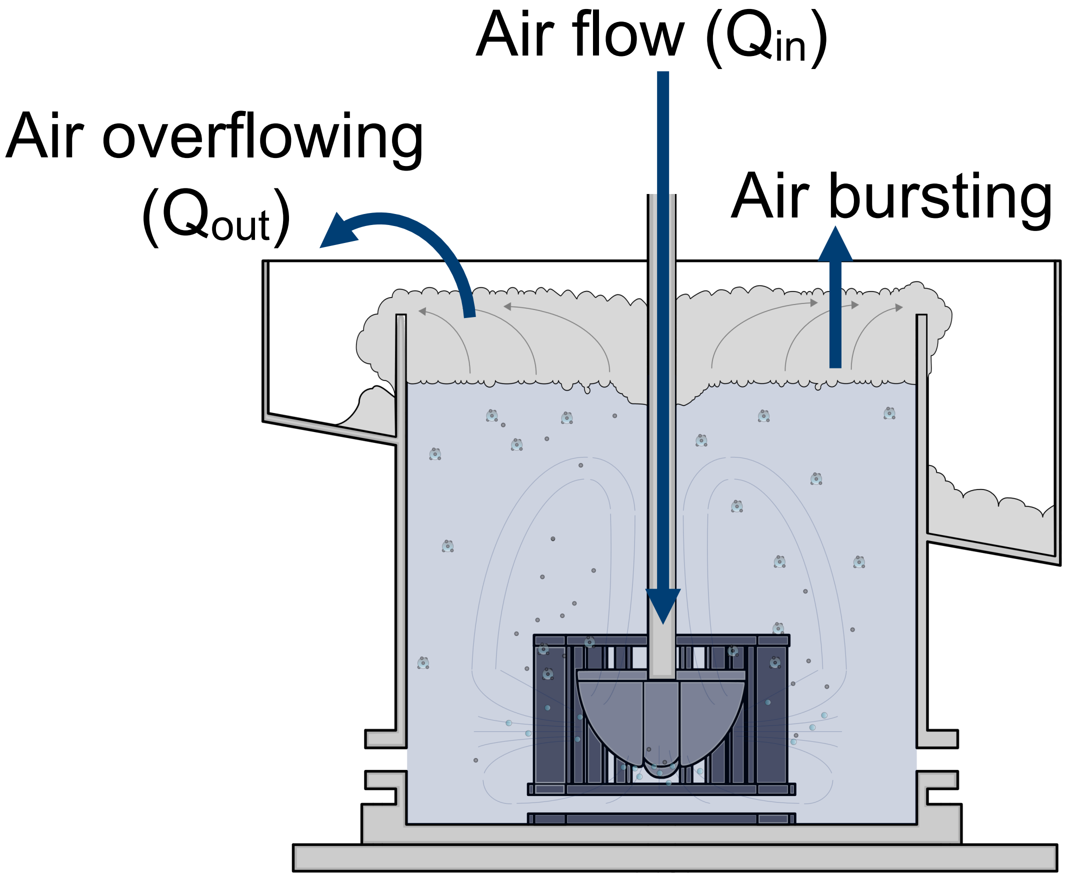
Imperial College London

Dynamic flotation model

Air recovery measurement

$$\alpha = \frac{v_f L_{lip} h_{froth}}{Q_{air,in}}$$

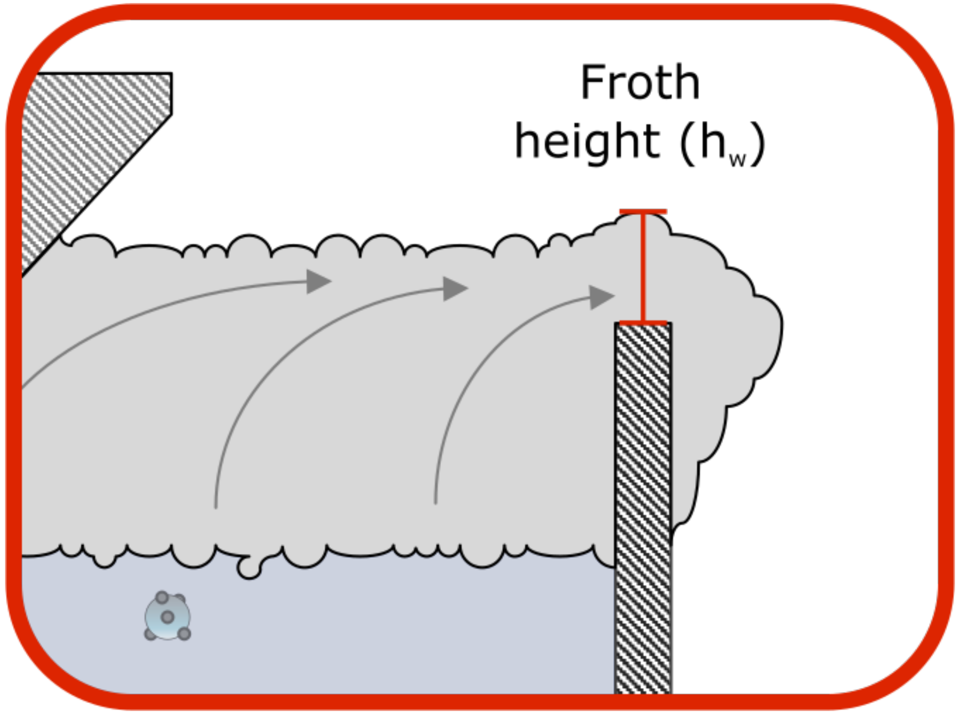


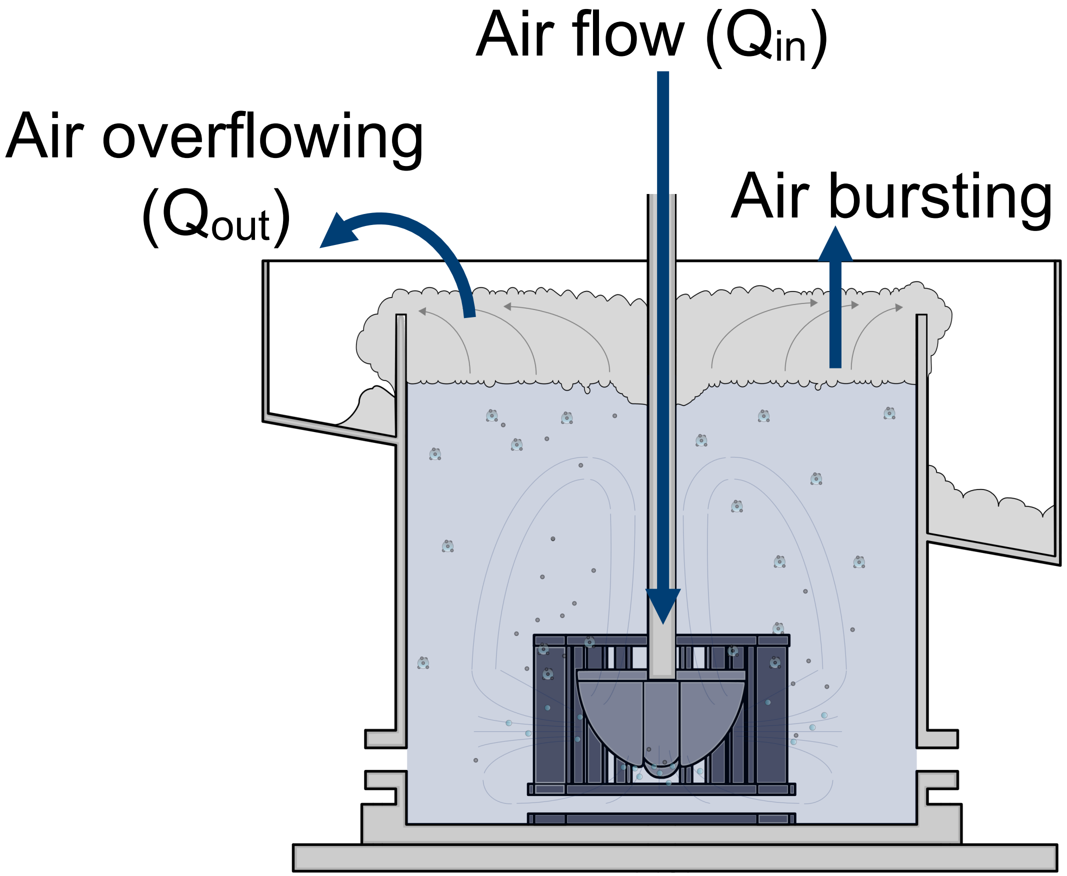


Dynamic flotation model

Air recovery measurement

$$\alpha = \frac{v_f \, L_{lip} \, h_{froth}}{Q_{air,in}}$$



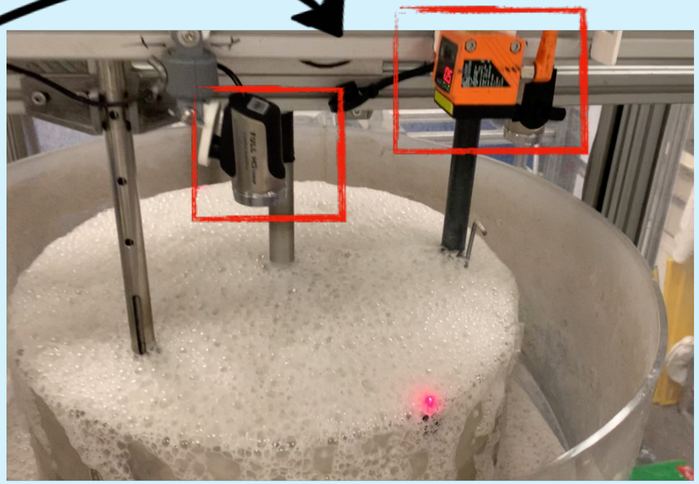


Imperial College London

Model validation

Experiments

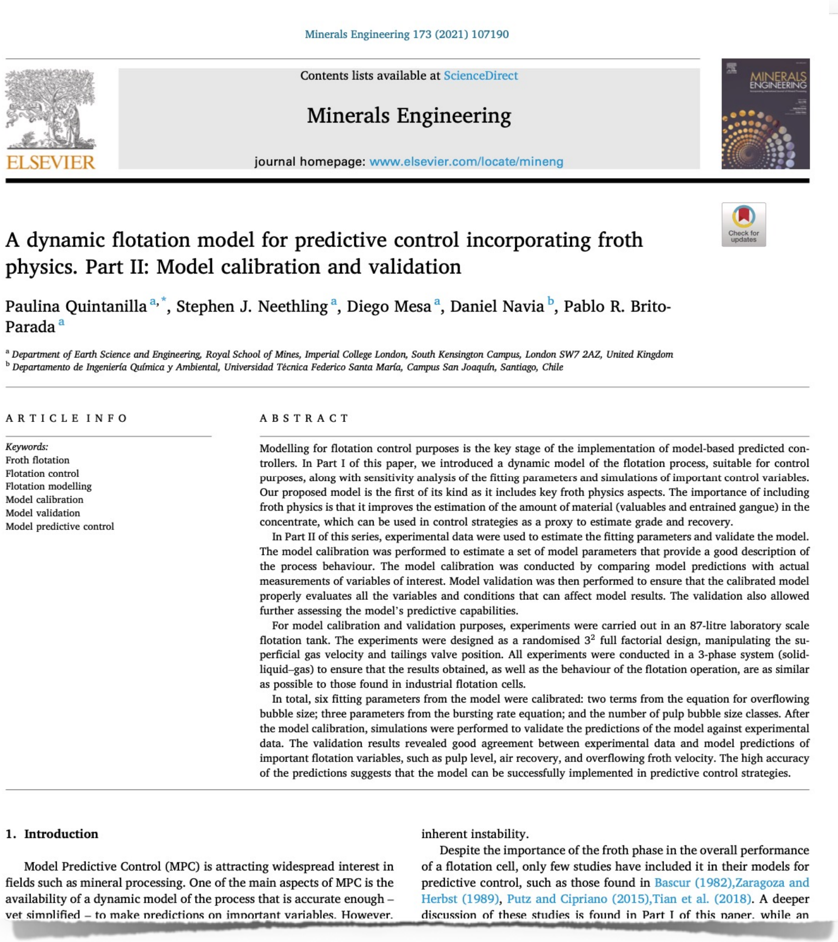
EXPERIMENTAL RIG



MEASUREMENTS

- ✔ Air recovery
- ✔ Pulp height
- ✔ Air and tailings flowrates
- ✔ Overflowing froth velocity
- ✔ Pulp bubble size distribution

87-litre laboratory-scale flotation tank at Imperial College London



Minerals Engineering 173 (2021) 107190

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

ELSEVIER

A dynamic flotation model for predictive control incorporating froth physics. Part II: Model calibration and validation

Paulina Quintanilla [a,*], Stephen J. Neethling [a], Diego Mesa [a], Daniel Navia [b], Pablo R. Brito-Parada [a]

[a] Department of Earth Science and Engineering, Royal School of Mines, Imperial College London, South Kensington Campus, London SW7 2AZ, United Kingdom
[b] Departamento de Ingeniería Química y Ambiental, Universidad Técnica Federico Santa María, Campus San Joaquín, Santiago, Chile

ARTICLE INFO

Keywords:
Froth flotation
Flotation control
Flotation modelling
Model calibration
Model validation
Model predictive control

ABSTRACT

Modelling for flotation control purposes is the key stage of the implementation of model-based predicted controllers. In Part I of this paper, we introduced a dynamic model of the flotation process, suitable for control purposes, along with sensitivity analysis of the fitting parameters and simulations of important control variables. Our proposed model is the first of its kind as it includes key froth physics aspects. The importance of including froth physics is that it improves the estimation of the amount of material (valuables and entrained gangue) in the concentrate, which can be used in control strategies as a proxy to estimate grade and recovery.

In Part II of this series, experimental data were used to estimate the fitting parameters and validate the model. The model calibration was performed to estimate a set of model parameters that provide a good description of the process behaviour. The model calibration was conducted by comparing model predictions with actual measurements of variables of interest. Model validation was then performed to ensure that the calibrated model properly evaluates all the variables and conditions that can affect model results. The validation also allowed further assessing the model's predictive capabilities.

For model calibration and validation purposes, experiments were carried out in an 87-litre laboratory scale flotation tank. The experiments were designed as a randomised 3^2 full factorial design, manipulating the superficial gas velocity and tailings valve position. All experiments were conducted in a 3-phase system (solid-liquid–gas) to ensure that the results obtained, as well as the behaviour of the flotation operation, are as similar as possible to those found in industrial flotation cells.

In total, six fitting parameters from the model were calibrated: two terms from the equation for overflowing bubble size; three parameters from the bursting rate equation; and the number of pulp bubble size classes. After the model calibration, simulations were performed to validate the predictions of the model against experimental data. The validation results revealed good agreement between experimental data and model predictions of important flotation variables, such as pulp level, air recovery, and overflowing froth velocity. The high accuracy of the predictions suggests that the model can be successfully implemented in predictive control strategies.

1. Introduction

Model Predictive Control (MPC) is attracting widespread interest in fields such as mineral processing. One of the main aspects of MPC is the availability of a dynamic model of the process that is accurate enough – yet simplified – to make predictions on important variables. However,

inherent instability.

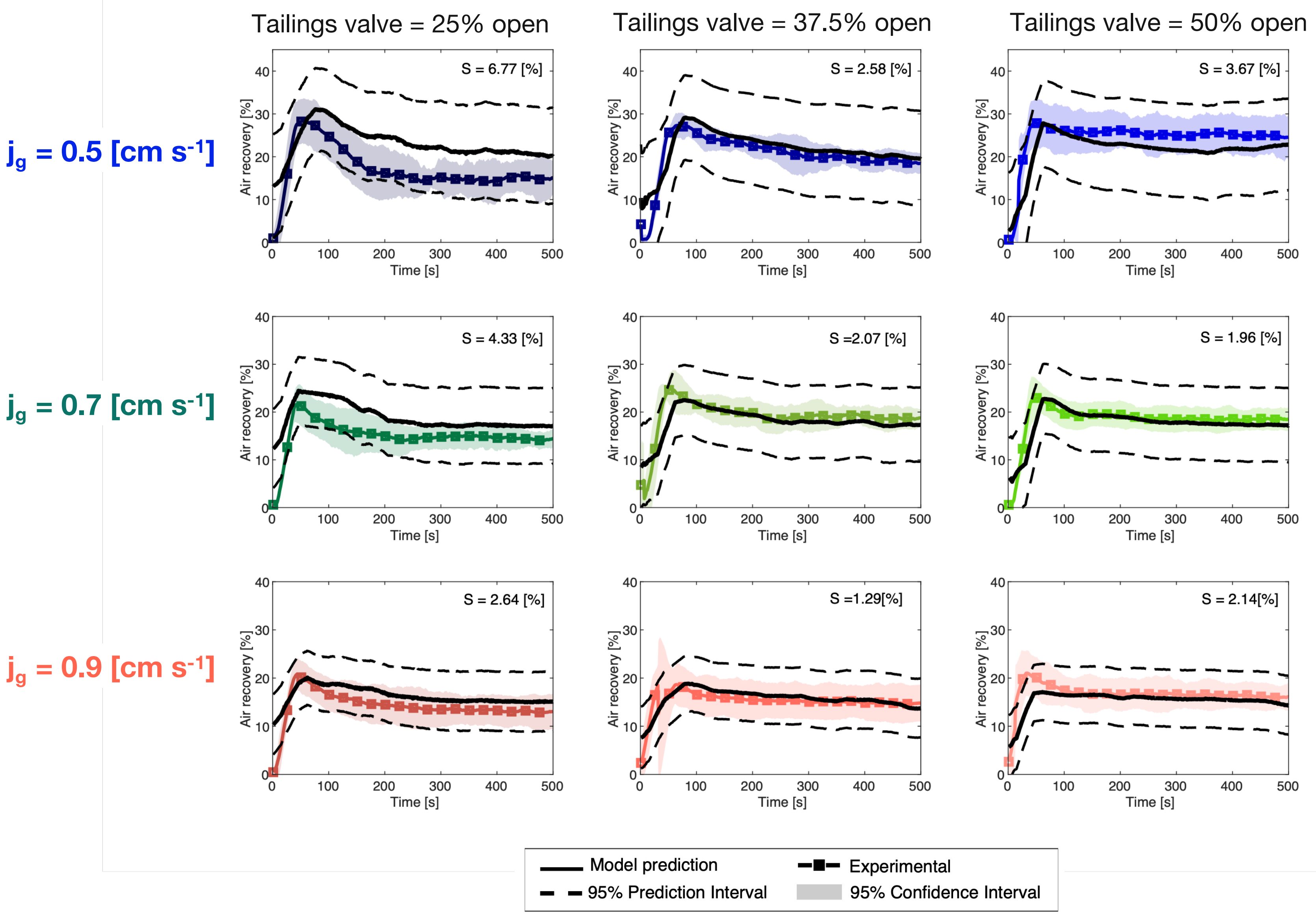
Despite the importance of the froth phase in the overall performance of a flotation cell, only few studies have included it in their models for predictive control, such as those found in Bascur (1982),Zaragoza and Herbst (1989), Putz and Cipriano (2015),Tian et al. (2018). A deeper discussion of these studies is found in Part I of this paper, while an

https://doi.org/10.1016/j.mineng.2021.107190

Imperial College London

Model validation results

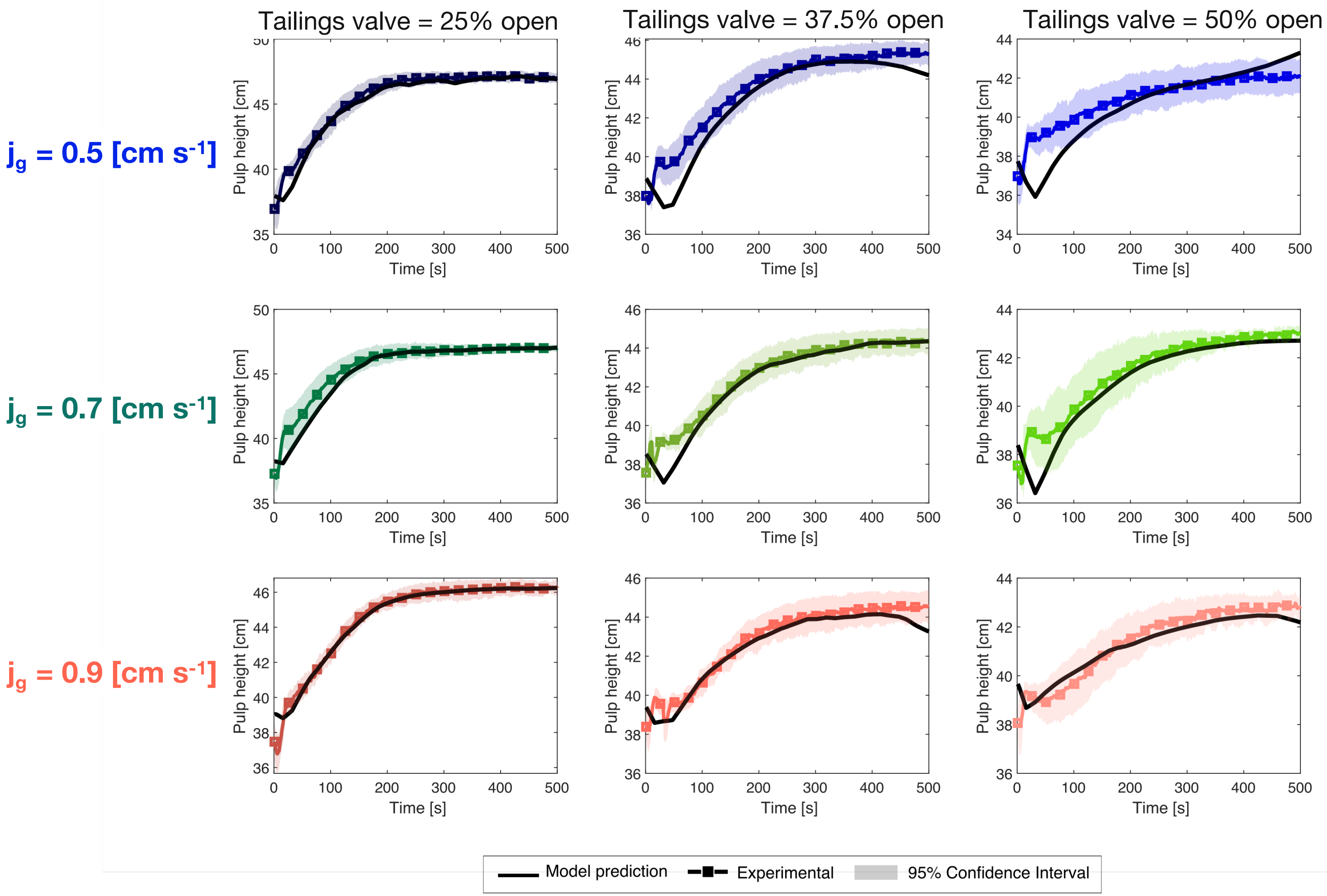
Air recovery



Imperial College London

Model validation results

Pulp height

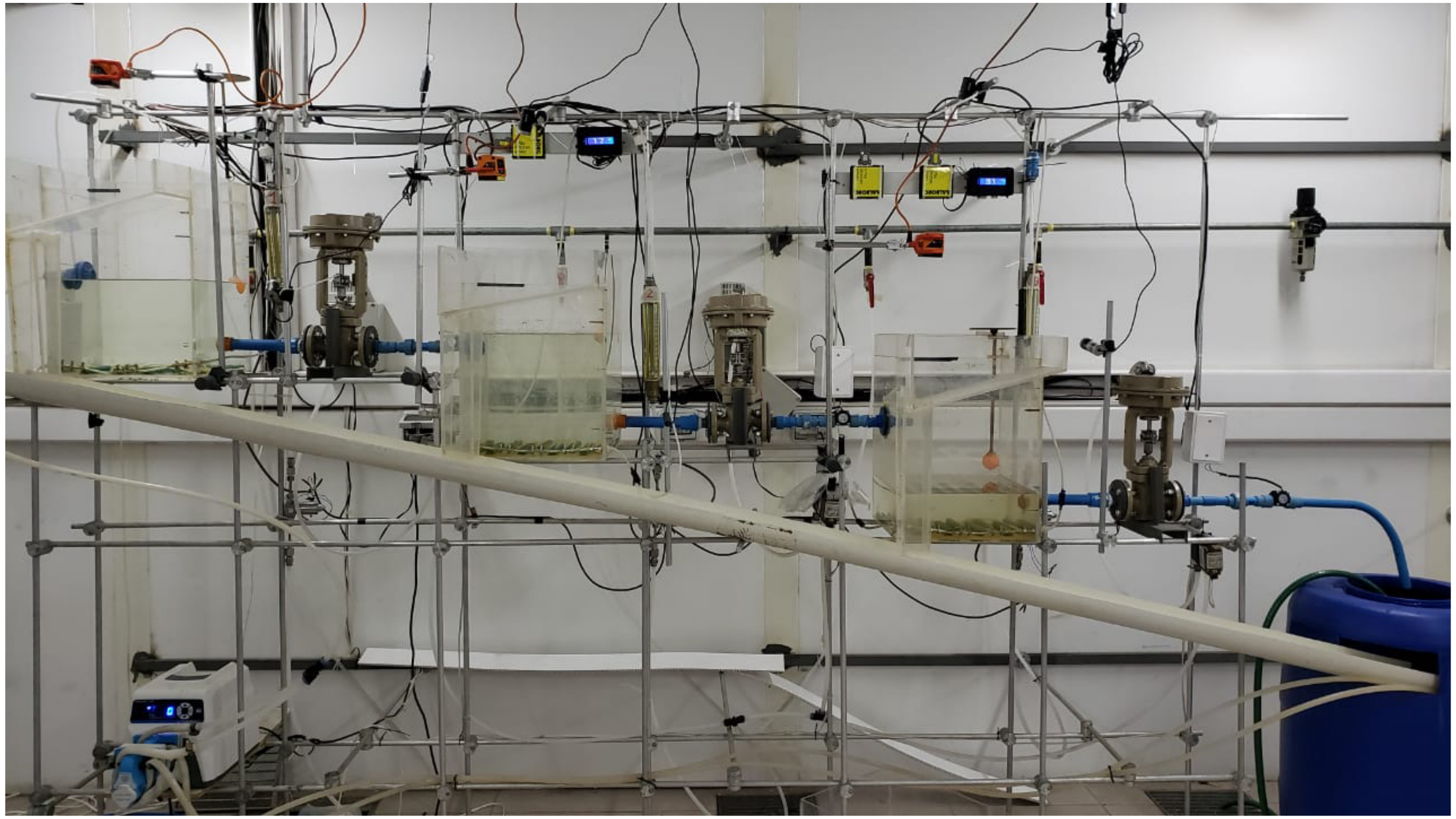


Imperial College London

Model Predictive Control

Laboratory-scale implementation

EXPERIMENTAL RIG



40-litre laboratory-scale flotation tanks at USM (Chile)

Bubbles in slow motion!

Imperial College London

Final remarks

Development of a new flotation dynamic model for predictive control, focused on the froth phase.

Air recovery for flotation control

Model validation revealed high predictive capability of critical variables.

2 degrees of freedom for control: Air and tailings flowrates.

Fully remote control implementation in Chile from the UK.

Imperial College London

Acknowledgments

BECAS CHILE

SCI
where science meets business

IOM3
The Institute of Materials, Minerals and Mining

Imperial College London

Advances in the Digitalisation of the Process Industries
IChemE – 20-21 October 2021

Development and validation of a dynamic model for flotation predictive control incorporating froth physics

Paulina Quintanilla *, Stephen Neethling and Pablo Brito-Parada

Advanced Mineral Processing Research Group **

Department of Earth Science and Engineering, Imperial College London

* p.quintanilla18@imperial.ac.uk

** @AMPRG_IMPERIAL