Tutorial 4: Plantwide control of a milling circuit

The Simulink model `MillingCircuit_openLoop.slx` simulates a milling circuit consisting of a ball mill, a sump, and a cyclone. The ore is fed to the mill at a rate MFO using a controllable conveyer belt. The ore is mixed with mill inlet water as well as the cyclone underflow stream before entering the mill. A controller maintains the ratio of the mill feed ore and the inlet water at an adjustable set-point of r_{MIW}. The mill speed ϕ_c can be manipulated, and the mill load J_T and mill power P_{mill} are measured.

The mill discharges to a sump, which also receives sump feed water at a flow rate SFW; the sump level S_{LVL} is measured. The slurry is pumped at a rate CFF to a cyclone cluster. The cyclone overflow is the product of the milling circuit. The particle size passing <75 µm (PSE) in the cyclone overflow is measured and represents the product quality. The model is fully described in *Validation of a dynamic non-linear grinding circuit model for process control* (Le Roux & Steyn, 2022, Minerals Engineering, 187). Figure 1 illustrates the circuit and includes all measured and manipulated variables.

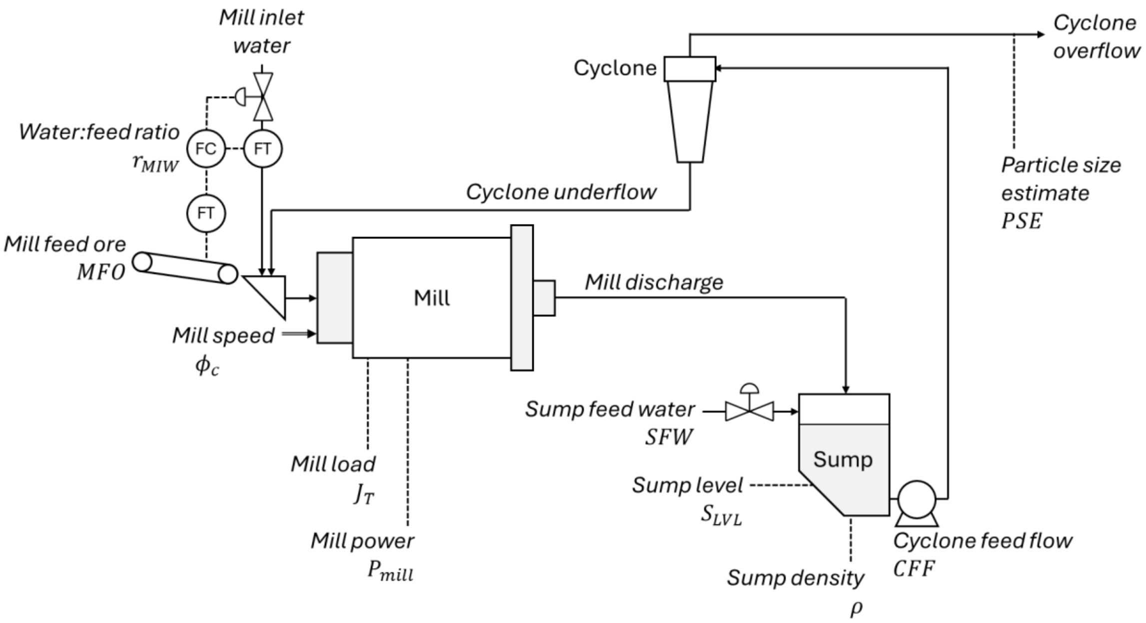

Figure 1. Milling circuit with recycle.

The milling circuit displays highly non-linear behaviour. Throughout the model, the components are distinguished as follows:

- Subscript r refers to rocks, where "rocks" are defined as solids which are too large to be discharged by the mill. Rocks therefore only occur in the mill feed ore and the mill itself.
- Subscript s refers to all solids that are small enough to be discharged by the mill.
- Subscript f refers to fines, which are solids smaller than the specification size of 75 µm.
- Subscript c refers to coarse product, which are all solids that are not counted as fines.
- Subscript w refers to water.

Solids as defined above accounts for both fines and coarse product, e.g., the volume of solids in the mill x_{ms} is equal to the volume of fines x_{mf} and the volume of coarse product x_{mc}, such that $x_{ms} = x_{mf} + x_{mc}$.

The model consists of mass balances for the most part, i.e., the rate at which a component accumulates in a unit operation is equal to the difference between the flowrate in and the flowrate out. The exception to this is the depletion of rocks and production of coarse and fine particles in the mill, and the split fraction in the cyclone cluster. These are qualitatively described below.

1. The mill discharge flowrate is inversely proportional to the ratio of solids to water in the mill, x_{ms}/x_{mw}. The slurry stops flowing when $x_{ms}/x_{mw} \geq 1.5$, thereby tripping the mill. Figure 2A shows the relationship between the total mill discharge volumetric flowrate and the solids to water ratio.
2. Rock consumption is directly proportional to the mill power draw P_{mill}. A fraction of the rocks consumed reports to the coarse product, while the remainder reports to the fines. Both the mill power draw and the fraction that reports to the fines is dependent on the mill load J_T, as shown in Figure 2B.
3. The mill power draw is linearly proportional to the mill speed, represented here as ϕ_c, the fraction of the critical mill speed.

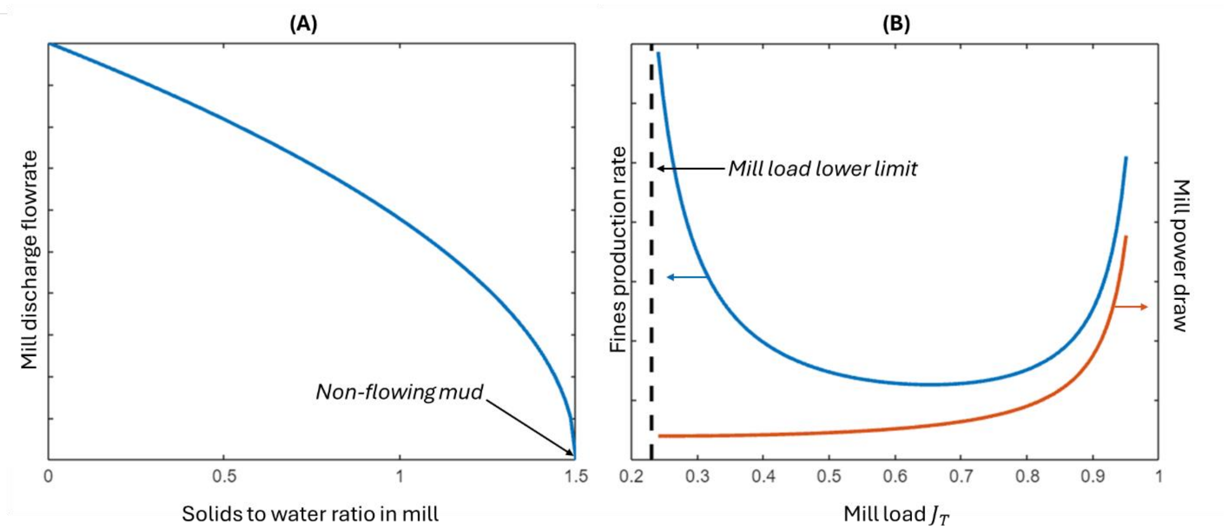

Figure 2. (A) Qualitative mill discharge flowrate as a function of solids to water ratio, with zero flow occurring when the solids to water ratio exceeds 1.5. (B) Qualitative fines production rate (blue) and mill power draw (orange) as a function of mill fill level. The dashed line indicates the minimum mill load.

4. The cyclone cluster separates fines from coarse product. The fraction of solids in the cyclone underflow F_u (which is recycled to the mill) depends on the fraction of fines in the cyclone feed, as well as the cyclone feed flowrate CFF, as shown in Figure 3. Increasing CFF therefore results in more coarse product to report to the underflow, thereby increasing the fines content in the overflow (PSE).

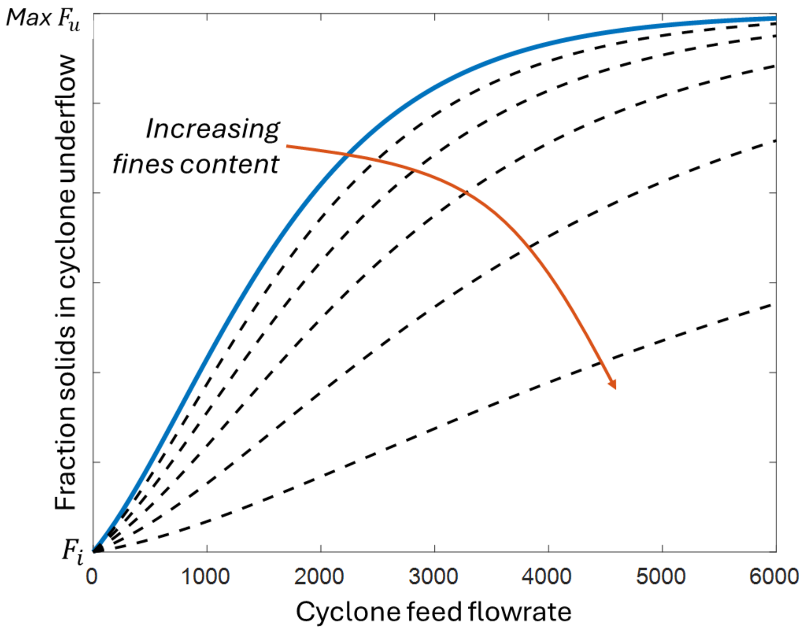

Figure 3. Fraction solids in cyclone underflow as a function of cyclone feed flowrate (x-axis) and feed fines content as indicated by the orange arrow. The symbols F_i and F_u represent the fraction solids in the cyclone inlet and outlet, respectively.

The system is subject to the following disturbances:

- The fraction of rocks (α_R) and fines (α_R) in the feed ore may vary.
- The rock consumption factor K_R, which relates the energy required to break rocks into finer particles, may vary. This represents variations in ore hardness.

This tutorial will focus on applying the plantwide control design procedure as presented by Skogestad in *Control structure design for complete chemical plants* (Computers and Chemical Engineering, 2004) and summarized in Appendix H of Process Dynamics and Control (2016, 4th ed.) by Seborg *et al.*, which is freely available from the Wiley website. You have the freedom to specify the production rate (i.e., sufficient upstream and downstream buffering capacity).

Note that one integrator inventory is present in the system. Consider a sensible MV to use for this inventory control, before proceeding with interaction analysis through RGA.

Multiple viable control structures may be possible in each case: experiment with different strategies, and critique each in terms of the system dynamics and control performance. Restrict yourself to the implementation of P-, PI-, or PID-controllers only.

A plantwide control structure for this system was developed by Le Roux and Craig and described in "Plant-Wide Control Framework for a Grinding Mill Circuit" (Ind. Eng. Chem. Res., 2019). You are welcome to consult this paper, or attempt to develop the control structure yourself and compare to the published work.