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Different perspectives of dynamics in comminution processes

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ABSTRACT

The performance of a comminution and classification process depends on the design and configuration of each process unit, the configuration of the plant, the design of the control and physical properties of the incoming feed. Comminution processes should be designed to have a stable and efficient production over a wide range of conditions. However, demands from the management, operational cost, investment, maintenance or any other related field can result in process alterations that are not beneficial for the stability of the circuit and, therefore, utilization and efficiency of the production. Furthermore, advanced process control and optimization rely heavily on understanding the dynamic behaviour of the process in achieving a more stable and consequently efficient process. This review aims to explore different dynamic aspects from particle, bulk, unit and process perspectives, their origin, and what consequences they may have on the operation. The aim is to illustrate a holistic view of process dynamics that should be considered when evaluating circuit performances and identifying risk zones that affect the process, considering the state-state performance and dynamic behaviour. Based on that, several dynamic related issues were formulated and ranked by experts within the field to get a subjective perspective. Issues such as process control design and configuration, ore variability, segregation and upstream disturbances ranked high in possible gains for comminution processes.

1. Introduction

Mineral processing is a multi-disciplinary process with physics, geology, rock mechanics, wear mechanics, mechanical engineering, chemical engineering, metallurgy and hydrodynamics interacting with each other. All these disciplines produce a high-grade concentration of a commodity with the desired properties from a large amount of low-grade ore.

An essential section of minerals processing is the size reduction or comminution of the ore. This is achieved with series of comminution and classification units such as crushers, mills, screens and hydrocyclones. The performance of each unit or a sub-process contributes to the total efficiency of the entire process. For each unit, the performance depends on the design, condition and configuration of each operational unit, the plantś configuration, the design of the control and physical properties of the incoming feed (Evertsson, 2000; Asbjörnsson, 2015).

In addition to the factors mentioned above, dynamics between different units also affect each unit's performance and the overall efficiency of the process. However, among experts of comminution and classification, there is not a clear consensus about what constitutes as dynamics. The processes are in a constant state of semi-equilibrium at different perspectives, meaning changes are happening within the system. This can be both discrete and gradual changes for multiple variables, occurring over time with different time perspectives. The work explores different dynamic aspects from the material, unit and process perspectives, their origin, and what consequences they may have on the operation. This is done by reviewing the published research to contextualize the abstraction level of dynamic occurring in comminution and classification processes. The aim is to illustrate a holistic view of process dynamics that should be used when evaluating circuit performances and identifying risk zones that affect the process, both considering the state-state performance and the dynamic behaviour.

2. Dynamics

The general description for a dynamics system is that there is a continuous rate of change in the system over time (t) with respect to an input (u) and a current state (x). Compared to steady-state, which is

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considered to be time-independent, the time derivative is equal to zero. Actual systems are often complex with multiple inputs, where the derivative (*dx/dt*) and the output (*y*) are a function of multiple input variables ($u_1,\ldots,u_n$) and internal state variables ($x_1,\ldots,x_n$), which are time-dependent (*t*), Eq. (1) (Ljung and Glad, 2002).

$$\begin{aligned}\frac{dx_i}{dt} &= f_i(x_1(t),\ldots,x_n(t),u_1(t),\ldots,u_m(t)) \\ y_i(t) &= h_i(x_1(t),\ldots,x_n(t),u_1(t),\ldots,u_m(t))\end{aligned} \tag{1}$$

For comminution processes, these changes originate from multiple sources, such as from the control system, operators influencing the system by changing setpoints, wear on critical components, changes in the orés mineralogy and much more.

2.1. Corpus analysis for minerals engineering

To get an overall perception of the term dynamic in the field of comminution, a Corpus analysis was performed on papers published in the journal Minerals Engineering between 2000 and 2020. In total, 206 articles contained search words: dynamic and comminution. The keywords analysis identifies reoccurring concepts such as performance-related concepts in particle size distribution, particle shape, mass flow, discharge rate, power and specific energy. Specific units: Ball mills, cone crusher, HPGR, SAG and their related components: lifters, liners, mantles. Particle-related aspects include properties, mineralogy, breakage, incremental damage, and bulk material aspects: charge motion, particle flow, and residence time. The numerical methods include the Discrete Element Method (DEM) and Smooth Particle Hydrodynamics (SPH), and steady-state and dynamic process simulations. This paper's core attention is on the operational and process-related perspective of the field, which includes feed rate, mass balance, load, wear, control, objectives, setpoints, speed, variations, etc. To summarise the key perspectives, the following abstraction level for the dynamics in a comminution process has been made: particle, bulk, unit and process. See Fig. 1.

However, each aspect is not independent and in most cases, there are interactions between those aspects that determine the comminution dynamics. For example, the breakage of particles is a consequence of interaction between particles or groups of particles with their surrounding geometry and its kinematics. Fig. 2 illustrates the interaction between the different aspects and an example of interaction effects between the aspects.

2.2. Particle dynamics

Particle dynamics are often associated with their breakage and their interaction with other particles or their surroundings. DEM has been extensively used to describe single particle breakage (Quist, Johansson et al., 2016; André, Potapov et al., 2019) and inter-particle breakage (Barrios, Perez et al., 2015) for different applications. The perception of time will also differ depending on the application; the applied strain rate on a particle can be defined as the rate of deformation (Saeidi, Mohsen Yahyaei et al., 2017). These can further be categorized as dynamic, quasi-static and static. Dynamic representing strain rate of 10^2 s^{-1} to 10^4 $s^{-1,}$ which includes blasting and impact breakage. Common comminution devices work be in a quasi-static load regime with a loading of 0.05–10 m/s, while fluid energy mills can reach loading velocities of up to 400 m/s (Tavares, 2007).

The inherent variation in the ores geological properties and characteristics will affects the unit performance. Such variation appears in different scales and can have different implications. At any given instant, particles with different characteristics are fed to the process, subjecting it to the variability of toughness, hardness and abrasiveness (Tavares and King, 1998; Faramarzi, Morrison et al., 2018). The large number of particles fed to most comminution and separation devices typically reduces the impact of this short-term variability dramatically. Exceptions to this are primary crushers and SAG mills, where a few coarse and tough particles can have a measurable effect on the machine performance that can last for several seconds or even minutes, respectively (Carvalho and Tavares, 2014). Evidently, the most noticeable impact of variation in the ore geological properties and characteristics on comminution performance is associated with a change in ore type and the variability in the mineral deposit. Such variations can impact plant performance in the time scale of hours, but mostly in days and weeks of plant operation. These variations are increasingly more challenging as plants are less prone to stockpile the ore fed to the plants. Indeed, any amount of variation needs to be considered relative to the robustness of processes (Robinson, 2002).

Characterizing the ore beyond average values of toughness, hardness, abrasiveness, moisture content, and mineralization, not only for a single sample but also for the entire deposit, can provide a valuable framework for understanding and predicting ore-dependent dynamic comminution processes. Designing the process on the basis of average values of these properties can lead to a need for process alterations later, as the ore body might change during the plant́s lifetime (Major, 2002). In Bueno et al. (Bueno, Foggiatto et al., 2015), the variation was

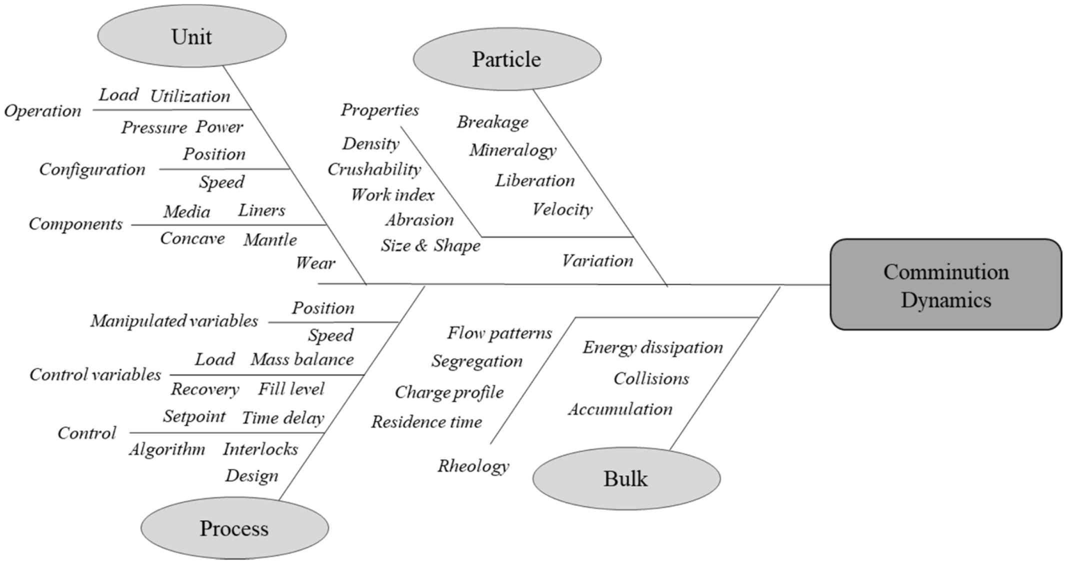

Fig. 1. Ishikawa diagram of the identified factors from the corpus analysis.

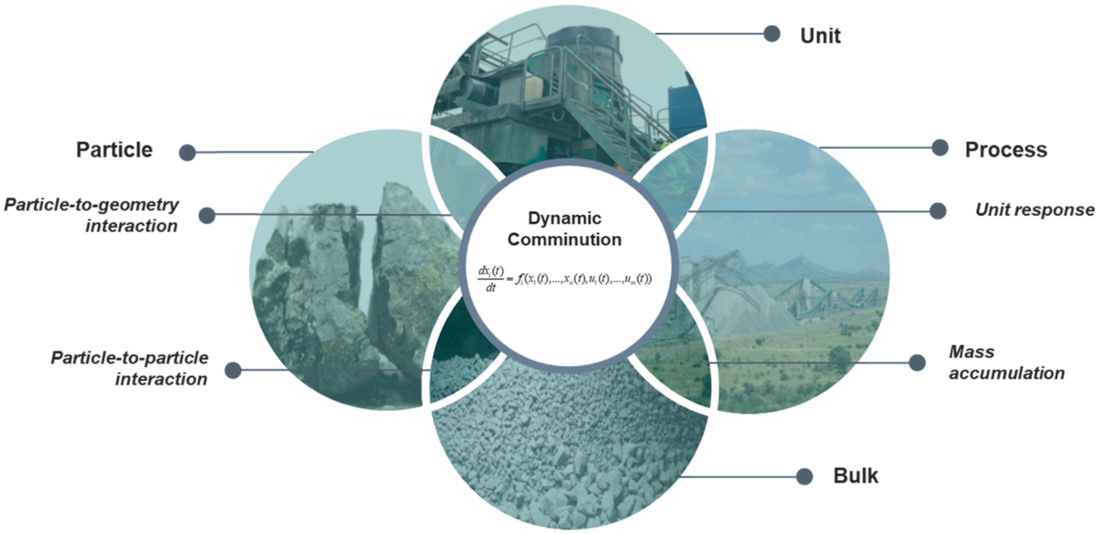

Fig. 2. Venn Diagram of system dynamics in comminution.

integrated into the process simulation with the Monte-Carlo simulation to identify the process's operational range. Variations in the incoming feed are often considered to be disturbing variables for the unit and process modelling (Itävuo, Jaatinen et al., 2011).

Another aspect that has seen some development in recent years is how to include mineral liberation into comminution models (Hilden and Yahyaei, 2019). Modelling breakage and liberation of composite material is key for one of the biggest challenges in process simulation: Integrating comminution and flotation models. Moreover, beyond the problems of dealing with multi-component models, there is the outstanding issue of agreeing on a common stream data structure so models can be connected to one another. A standard stream structure must be agreed upon if a dynamic simulation platform is to be created with the available models.

2.3. Bulk dynamics

Bulk material behaviour is defined by accumulation and the flow of granular material, resulting from particles interactions and the configuration of its surroundings. The material can cause numerous issues in different units resulting in a lower overall process performance (Powell, Benzer et al., 2011). Issues caused by feeding arrangement, flow patterns, segregation, residence time, etc. DEM is the most common approach to study and quantify particle–particle interaction in different units such as crusher (Quist, 2017), mills (Cleary, 2001) screens (Davoodi, Asbjörnsson et al., 2019), sumps and bins (Cleary and Sawley, 2002). Experimental works rely on image analysis (Quist, 2017) and tracers to measure selected particles' motion patterns (Marigo, Davies et al., 2013). Most published dynamic process simulations include the accumulation of bulk material as the perfect mix tank model (Asbjörnsson, 2015). However, for steady-state process simulations, inventory models have also been incorporated to include bins in software solutions as the IES. There are few publications where more detailed bulk material models have been implemented to get a better process response. Such models are based on horizontal plug flow layers (Itävuo, 2009) and vertical segmentation in 2 and 3 dimensions with variable transport velocity functions (Asbjörnsson, Hulthén et al., 2012; Ye, Yahyaei et al., 2019). The rate of change in bins and hoppers put an additional demand on the control system configuration. Bins and hoppers need to be able to suppress process variations, not amplify them.

Most processes have several crushing/milling stages to gradually reduce the size of the ore for a certain purpose. Large bins or stockpiles are often placed between each stage as a buffer in an effort to make each stage an independent circuit. Stockpiles, bins and hopper level patterns are always directly related to the control strategy in the circuit and the stability of the process. Four common patterns often reoccur. These are a consequence of level control, on/off operation, low volume utilization and stochastic operation. The rate of change for the level needs to be in relation to the size of the volume. Higher the rate, the faster the bin will fill up, become empty or trigger an interlock. Analyzing the level and rate of change of the level identifies the balance between the incoming and outgoing mass flow. In the On/Off operation, the material flow from the bin is relatively stable, with the incoming feed having a discrete behaviour. This creates a significant disturbance amplification. However, this can also change over time as units will have different operating conditions and material properties for the bulk material will change.

2.3.1. Rheology

The rheology of dry granular material is dependent on the geometry of the flow, wall roughness, flow rate, shape and size distribution of the grains where the different flow regimes are determined by momentum transfer and energy dissipation occurring in direct contact between particles and with their surroundings. There are two dominating regimes for the material flow, a quasi-static phase and a liquid phase, where the transition between the regimes is determined by the shear stress acting on the particles (Fall, Ovarlez et al., 2015). Different flow patterns can occur in bins and silos, resulting in different residence time distributions and mixing (Standish, Liu et al., 1988). In course comminution, the performance of the units is significantly influenced by stratification and segregation. For screens, the main principle of screening is stratification (Ogunmodimu, Govender et al., 2021). While segregation in crusher or HPGR feed will cause excessive power and pressure fluctuation for crushers (Gröndahl, Asbjörnsson et al., 2018) and skewing for HPGRs (Hannot, Van Der Meer et al., 2019).

In the wet part of any comminution/classification circuit, an important additional variable must be considered: slurry rheology. It is influenced significantly by the percentage solids in the slurry and size distribution, besides more subtle effects, including particle shape, composition and temperature (Kawatra and Eisele, 1988). Typically, from a Newtonian response at low percentage solids, mineral slurries exhibit dilatant behaviour up to approximately 50% solids. At higher solids concentrations, such slurries will first transform to a pseudoplastic nature and subsequently develop a yield value (Austin, Klimpel et al., 1984)

Slurry rheology has been known to influence several aspects of particle behaviour during processing, in particular owing to its effects on particle settling velocity and resistance to the flow of slurry inside the devices.

Slurry rheology influences size reduction in a grinding mill at the microscale level. When grinding media approach each other in a collision, fluid and possibly particles may be squeezed out of the gap between them depending on suspension viscosity (Peukert, 2004). Also, at higher viscosities, grinding media become coated with a layer of slurry, which helps prevent media collisions without undesirable particles. Under extreme rheological conditions, namely high yield values of non-Newtonian behaviour, grinding media can adhere to the mill shell (Fuerstenau, Venkataraman et al., 1985). This can cause media to centrifuge at mill frequencies below the nominal critical speed, resulting in a drop of mill power and breakage rates. In general, maximum fines production, as well as maximum power draw, are achieved just below this condition. Besides breakage, higher slurry viscosities can lead to poor slurry transport in the mill, which can result in its overload.

Classification in wet systems is also directly influenced by slurry rheology. In hydrocyclones (Kawatra, Bakshi et al., 1996; Tavares, Souza et al., 2002; Narasimha, Mainza et al., 2014), high-frequency screens (Mabote, Mainza et al., 2019) and screw classifiers (Fuerstenau and Han, 2003) the cut size significantly increases as the apparent viscosity of the slurry increases. In hydrocyclone it has also been observed that the water split to the underflow increases with slurry viscosity (Kawatra, Bakshi et al., 1996). In extreme rheological conditions, roping and flaring can occur in hydrocyclones.

Besides its obvious effect in small-scale particle dynamics, slurry rheology can have an important role in the context of circuit dynamics, owing to its non-linear response to several of the variables that affect it. For instance, a sudden increase in either solids concentration or fineness can result in a measurable increase in apparent slurry viscosity. Such higher apparent viscosity will result in an immediate reduction in settling velocity of particles in hydraulic classifiers, coarsening of the hydrocyclone overflow, but also an increase in water split to the underflow. Suppose the hydrocyclones operate in closed-circuit with a ball mill. In that case, this excessive amount of fine material in the feed will lead to a reduction in mill efficiency, causing difficulties in downstream separation processes. Such complex interactions require careful control of rheology in these circuits (Yanatos, Lisboa et al., 2002). In tumbling mills, this increase in slurry rheology may push milling to a very inefficient domain of operation, given the cushioning effect offered by the slurry and the reduced power. In the case of gravity-induced stirred mills, this increase in slurry viscosity can lead to a significant increase in power without necessarily increasing the fineness of the product. Seasonal temperature variations can create yet another time-dependent effect of rheology in classifiers, given the ambient temperature variations in winter and summer months in plants operating at high latitudes (Kawatra and Eisele, 1988).

2.4. Unit dynamics

Unit dynamics represent how each single operational unit response to the changed state. Changes can be caused by actuator response, ore variability, changed configuration, such as calibrations or maintenance traditionally needed in a comminution and classification process. Each unit consists of a mechanical design driven by the configuration of different types of actuators with respect to the stream properties. See Fig. 3 for a generic system structure.

Each actuator enables a manipulated variable to be adjusted by the operator or process control during operation, changing its functional performance. These are often related to speed or position: such as feeder frequency (Muller, de Villiers et al., 2010), mill speed (Herbst, Robertson et al., 1983), crusher speed and CSS (Hulthén, 2010), etc. Any change of the manipulated variable will create a transient condition from one state to another. The response will be affected by the change's quantity, the unit design and configuration and the amount of material within the system. Units such as Crushers and HPGRs are reactive units that can be adjusted directly as a counter measure to a change in operation condition while mills and hydrocyclones are *retro*-active units where adjustments should be made when the circuit has achieved stability. The systems responses is an direct indication of the unit and process performance and is used as control variables and for process objectives. These are online performance values that are available for the operator or the control system as single metrics, such levels (Itävuo, Hulthén et al., 2017), flow rates (Hodouin, Jämsä-Jounela et al., 2001), power draw (Guerrero, Bouchard et al., 2016), product size (Maritz, le Roux et al., 2019) etc. or a combined metric such as yield (Hulthén and Magnus Evertsson, 2011), split ratio (Itävuo, Vilkko et al., 2013) or liberation (Pérez-García, Bouchard et al., 2019).

2.4.1. Crushers

For crushers, the response is fast from a unit perspective. The hydraulic system can change the CSS with approximately 1 mm/s (Asbjörnsson, Erdem et al., 2020) with a fixed displacement pump while each eccentric rotation happens at 0.17–0.25 s (Evertsson, 2000), generating a compression rate of 0.17–0.70 m/s depending on the eccentric throw. The material is compressed approximately 8–12 times, which counts for approximately 2 s, neglecting the residence time in the hopper above the crushing chamber (Evertsson, 2000). Pressure and power are directly related to the amount of breakage achieved in crushers. The mantle wear profile depends on the material abrasion characteristics and how the crusher is operated. The wear rate on the mantle can be around 0.5–1 mm/hr (Asbjörnsson, Hulthén et al., 2012; Bearman and Briggs, 1998), making it necessary to adjust frequently, a preferable couple of times during a shift, if not automatically

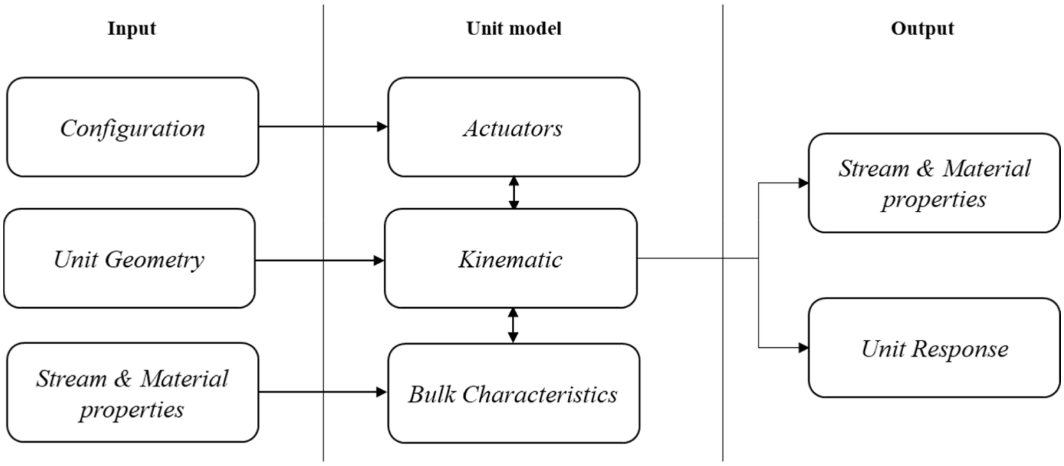

Fig. 3. Generic functional modelling structure.

compensated (Asbjörnsson, Bolander et al., 2019). The mantle can be continuously adjusted if the crusher is installed with a hydraulic system and operating under load control (Asbjörnsson and Åberg, 2010). How the crusher is operated can change the mantle's lifetime from 220 h to 280 h (Hultén and Evertsson, 2008).

2.4.2. *HPGRs*

HPGRs have a more reactive response to changes in the incoming feed compared to crushers. HPGRs utilizes a system of hydraulic cylinders and accumulators to keep a floating roller in place while a second fixed roller is suspended in the frame. Active dampening is applying through a controlled throttle valve which is pressure-dependent (Johansson and Evertsson, 2019). HPGRs apply a single compression between the two rotating rollers, with a compression ratio of being a function of the operating gap and the compression angle, which is generally around 6–10 degrees (Schönert, 1988). Given a rotating speed of 10–20 rpm and diameter of the rollers of 0.8–3.3 m gives a slow compression rate between 0.04 and 0.54 m/s. Both power and pressure directly related to the force acting on the particle bed to achieve breakage as for crushers. The majority of the residence time is a function of the capacity and the volume of the material in the hopper, the same as for crushers. If there are any segregation issues in the incoming feed, the rollers will skew to compensate for the uneven force distribution acting on the rollers. The breakage performance is directly connected to the pressure profile over the rollers. The addition of cheek plates or flanges creates a more even distribution over the length of the roller.

2.4.3. *Mills*

Mills in comparison are rotating around 3–15 s per rotation with a material response highly dependent on the mill fill level. It can take the mill up to several minutes to reach a new steady-state operation after a step change, how fast it can to stabilize depends on the step size and the current state of the charge. Change in speed will cause a sudden surge in power draw, charge behavior and discharge rates. Superficial residence time can vary between 1.5 min up to 7.5 min for different mills (Morrell, 2001). However, different size classes will segregate and have different transport velocities (Mwansa, Condori et al., 2006). As such, depending on mill type, feed size, rate, size distributions as well as slurry rheology, may be responsible for significant shifts in both throughput and product size, with a severe impact in downstream operations. In contrast to crushers, process dynamics associated with wear are not as significant. Indeed, wear rates in mills are at around 10–20 μm/hr for the balls (Jankovic, T. Wills et al., 2016), up to 1.4 mm/day for the liners (Toor, Powell et al., 2011). Liner wear varies significantly along the mill axis, which results in speed adjustments regularly and finally relining, which can happen after approximately 4–5 months (Toor, Powell et al., 2011). The corresponding downtime can vary between 8 and 96 h.

2.4.4. *Screens*

Vibratory screens are passive units that are not actively controlled. However, the separation of the mass flow is affected by loading, feeding arrangements, and the condition of the unit. The efficiency of screens experiences a non-linear relation with regards to load. The efficiency increases up to about 80 % of the designed loading capacity and starts to drop after that (Allis-Chalmers). The residence time of the material will depend on the length of the screen and the material transport velocity. The transport velocity is a function of frequency, inclination and stroke and can vary between 0.1 and 0.6 m/s (Soldinger, 2002). In operation, screen performance can be significantly reduced with improper engineered feeding arrangement and moisture, reducing the available open area due to clogging.

2.4.5. *Cyclones*

Hydrocyclones operate in clusters and their classification performance is a vital part of any grinding circuit. Hydrocyclones are static units and for given dimensions, the cut size is dependent on the vortex finder and spigot diameter, feed solids concentration and flowrate. To obtain a consistent cut size, the hydrocyclone should be operated with consistent volumetric feed flowrate and slurry pulp density by adjusting the number of operating hydrocyclones or adjusting the water valves. The cyclone feed sump should be large and deep to allow fluctuations in the total flow to the cyclone cluster, while opening and closing hydrocyclones would permit each cyclone in the cluster to operate with a reasonably consistent feed flow rate (Mainza, 2017). Pressure is a direct indicator of the feed volumetric flow rate and any deviation in pressure will alter the hydrocyclone performance. Increasing the importance of understanding the influence of geometrical dimensions (Narasimha, Mainza et al., 2014). The particles will experience a residence time distribution range from 5 to 25 sec (Stegowski and Leclerc, 2002). However, the range can be larger depending on the size of the hydrocyclone and the internal fluid dynamics. Due to the centrifugal flow and ore on the stream, the internal surfaces of the cyclone are prone to wear. Having a combination of rubber and ceramic liners can achieve an operating lifetime of 13.000 h (Flintoff and Knorr, 2019).

2.4.6. *Response and residence time*

How fast each unit responds to changes in the operating condition depends on the mechanical design, kinematics, and bulk material characteristics. In Fig. 4 a general mapping of the different time perspectives for the different operational units has been created. Breakage principles compression, impact and shearing, demonstrated in grey, as well as the breakage propagation itself. Unit response to a change in the feeding conditions is in green. Adjustments associated with a change in operating conditions marked in blue, both short-term and long-term adjustments. Each unit's approximate residence time, which depends on their size and operational strategy, is marked with yellow. Finally, in red, there is monthly planned maintenance

2.4.7. *Unit model calibration*

Although models have had decades of development, more robust and first principle models are required. These models would require fewer fitting parameters (model calibration factors) and rely more on equipment design and operating parameters, which are more accessible. Computational Fluid Dynamics and Discrete Element Method models achieve this, but the computational load required to run them is prohibitive for real-time applications. However, complex and realistic models can serve as an off-line platform for process modelling development (Narasimha, Mainza et al., 2014).

As in steady-state models, dynamic models have parameters that need to be fitted to the plant data, and most importantly, for some applications, this calibration has to occur online (Reyes, Yahyaei et al., 2020). Calibration requires thus the availability of reliable sensors. This can be a challenge for some operations with very little instrumentation. It is still not possible for some variables to measure them directly (e.g. filling inside a mill). Soft sensors and new state-estimation techniques answer these difficulties (Miriyala and Mitra, 2020). Soft sensors can also help models account for equipment wear, making design parameters time-dependent (e.g. spigot size in hydrocyclones, mill diameter, etc.).

2.5. *Process dynamics*

The performance of a comminution process depends on each process unit's design and configuration, the configuration of the plant layout, configuration, the objective of the control and physical properties of the incoming feed. Every process is subjected to changes in performance over time due to an altered state of different units due to factors such as natural variations, unmatched, inappropriate or degrading unit performance and stochastic events, often categorized as disturbances.

The initial step for understanding the process is to define the connections and the limitations of the process by mapping out the physical and logical connections throughout the circuit. This means identifying

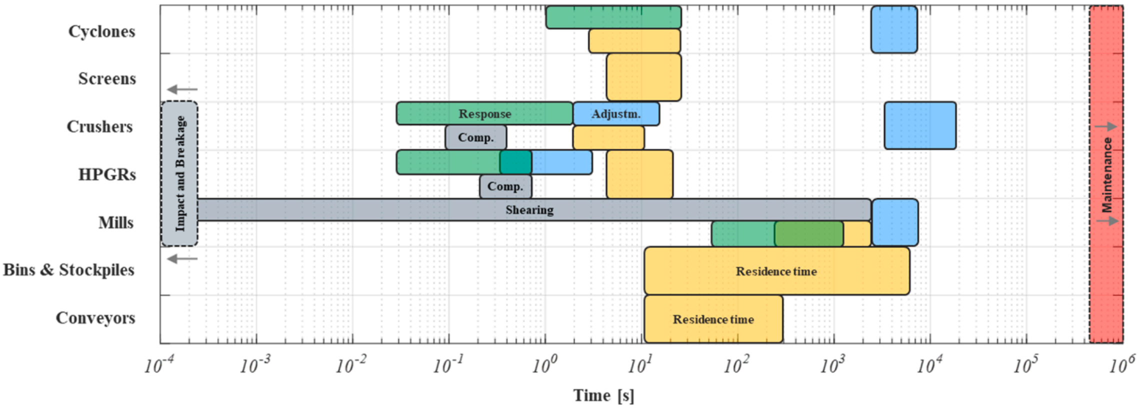

Fig. 4. Time perspective for different units.

and listing the physical connection (x) between all units and their relationship with manipulated (M) and control variables (C), as well as the interlocks (I) used for the process control. See Fig. 5 for an example process layout and its corresponding physical and logical correlation matrix in Fig. 6.

In the example process, each crushing state is marked within a darker square. Within each crushing stage, there is a clear interdependency between units, both physically and logically. In some cases, as for the crusher, there are both manipulated variables and control variables in a local control loop, the CSS as manipulated variables and either power or pressure as control variables.

The focus when debottlenecking a process is to ensure stability and process robustness. When it is stable, then the focus can shift towards gradual improvements such as increased throughput. Increasing throughput in an unstable process can further increase variability and uneven loading conditions on the units, which can result in lower reliability and availability in a long-term perspective

2.5.1. *Process control*

For a simple open-circuit configuration, the stability of the process is easier to achieve since the bottleneck can be identified as the unit with the lowest capacity that is limiting the flow. Then it is a task of matching the manipulated variable with a single control variable and develop an appropriate control strategy so that a stable process operation can be achieved. How the controllers respond will depend on the control objectives, system dynamics, selection of control and manipulated variables, and the controllers' configuration (Dorf and Bishop, 2001). If the configuration of the controllers is insufficient, then the process will experience reduced performance. For larger, more complex closed-circuit configurations, the stability can be harder to achieve as the circuit might have multiple parallel flows, recirculating mass, larger lag times, partial integration of different stages and a mitch match between manipulated variables and control variables. From a simulation point of view, what-if scenarios are valuable for identifying the critical components (Brown, Steyn et al., 2016). Or even optimization to identify the most optimum configuration of the process to ensure stability as well as product throughput (Bhadani, Asbjörnsson et al., 2018)

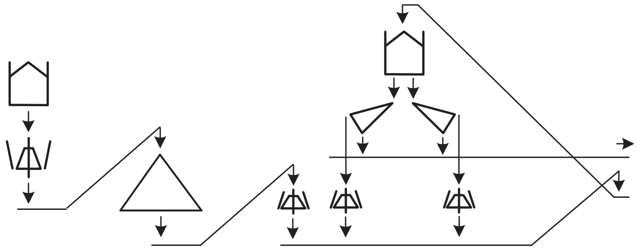

Fig. 5. Example process.

	Bin	Feeder	Gyratory	Conveyor	Stockpile	Feeder	Conveyor	Crusher	Conveyor	Conveyor	Bin	Feeder	Feeder	Screen	Screen	Conveyor	Crusher	Crusher
Bin		xI																
Feeder	xI	M	xC	I	I													
Gyratory		xC	MC	x														
Conveyor		I	x		x													
Stockpile		I		x		xI												
Feeder					xI	M	x	C	I	I	I							
Conveyor						x		x										
Crusher						C	x	MC	x									
Conveyor						I		x		x		I	I				x	x
Conveyor						I			x		x	I	I					
Bin						I				x		x	x					
Feeder									I	I	x	M		x		I	C	
Feeder									I	I	x		M		x	I		C
Screen												x				x	x	
Screen													x			x		x
Conveyor												I	I	x	x			
Crusher									x			C		x			MC	
Crusher									x				C		x			MC

Fig. 6. Example process physical and logical correlation matrix.

Most applications, including process dynamics, are focused on demonstrating the benefits of different control strategies by rejecting defined disturbances by changing the manipulated variables to achieve a particular control objective. These could include, for example: maximize recovery, maximize flow rate, minimizing variability, minimize specific energy or minimizing downtime etc. The benefits from process control strategies are mainly for process stability improvements, increased throughput and reduction in energy consumption (Wei and Craig, 2009). This includes implementation such as regulatory controllers (Airikka, 2012), Model Predictive Control (Johansson, 2017), Expert systems (Leiva, Arcos et al., 2018), Fuzzy Logic (Moshgbar, Parkin et al., 1995) and more. The evaluations of the process dynamics are limited, with many publications relying on visual validation while some present a single value performance index such as average performance with different KPIs (Bhadani, Asbjörnsson et al., 2020) or with an error estimation, such as R^2, root mean square error and relative error.

2.5.2. *Events and maintenance*

Discrete events are not often the focus within comminution modelling. This is more common in research focused mining and maintenance, where it can be characterized as discrete process operation (Ozdemir and Kumral, 2019). However, unit availability and reliability are a large part of the process utilization. As the size and complexity increase, unit failure's implication becomes ever more critical (Barabady, 2005).

Methods such as Pain analysis (Kullh and Älmgran, 2013) can be useful diagnostic tools for process improvements looking into failure frequency and downtime.

2.5.3. Operators

Operators still have a significant influence on the process. A large number of processes do rely on manual control or do encounter manual intervention when the perception is that the control system is not working as it should be. One of the key aspects of the operator losing control is due to a lack of in-depth insight into the critical process dynamics (Li, McKee et al., 2011). There is a complex interaction between the process and the people involved in operating the process, which is most often overlooked. The information from the instrumentation needs to be presented in the right way to enable efficient decision making. Operators make decisions based on their experiences. However, how fast they are able to respond is related to their cognitive capacity. When the cognitive load increases or the task efficiency decreases, the human efficiency decreases (Kumar and Kumar, 2019).

3. Operational perspectives

Perception is dependent on the experience of the viewer. Understanding where the problem originates from is one key factor. Being able to compensate for that is another. The view of what is a common problem, easy or difficult to fix and what has the largest impact on the process depends on each individual experience out in the field (Fig. 7), what background they have (Fig. 8) and what type of process they have worked with. To capture these perspectives, a survey was performed based on the findings from the previous chapter. 21 Experts with different backgrounds and from different fields of the process were contacted and asked to give their opinion. Their background and expertise varied to get a more holistic view.

The following issues were formulated for the experts to rank from different perspectives.

1. Inappropriate design of the process control
2. Untuned process control configuration
3. Inappropriate process control setpoints and limits
4. Inappropriate design of the local unit control
5. Untuned local unit control configuration
6. Upstream disturbances from the preceding process
7. Downstream disturbances from subsequent process
8. Inappropriate unit variables configuration
9. Under-dimensioned units in the process
10. Over-dimensioned units in the process
11. Excessive wear on critical components
12. Unwanted segregation caused by material handling
13. Undesirable flow patterns in bins hoppers and mills
14. Unforeseen material hold-up or blockage in unit operation
15. Inappropriate feeding arrangement
16. Overloading of units during operation
17. Under-utilization of units during operation
18. Abnormal failure rate of auxiliary systems
19. Ore variability from ROM
20. Unstable operating pressure, power or other control variables

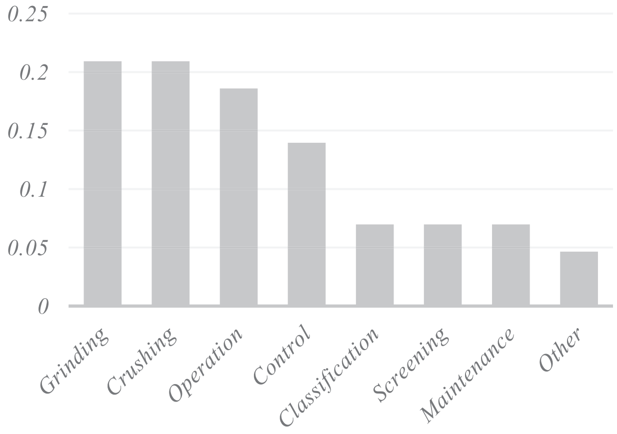

Fig. 7. Distribution of the experts respective fields.

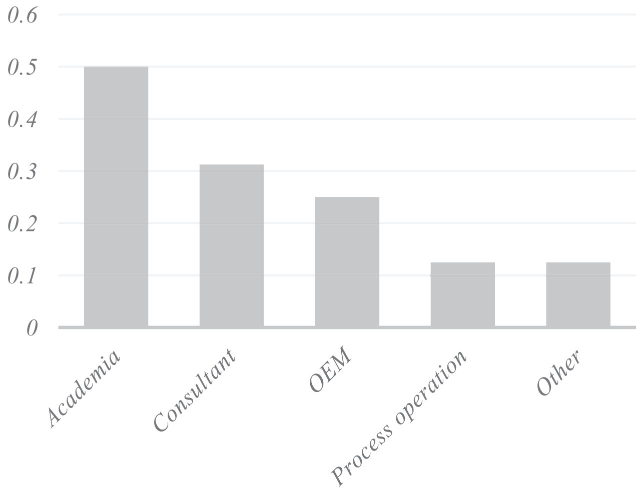

Fig. 8. The distribution of the experts' backgrounds.

The survey resulted in a ranking of factors with regards to the different perspectives. See Figs. 9–11. For the most common issues, the inappropriate design of the process control, unwanted segregation and ore variability from Run-of-Mine were ranked as most common.

For the potential impact on the process, both inappropriate design of the process control and undesirable segregation were ranked at the top, both being moderately hard to compensate. For the most difficult issues to mend came down to under-dimensioned equipment in the process and ore variability. While easiest to adjust came to untuned control loops and configuring and determining more appropriate setpoints and levels for the control system.

Looking into those factors together give a potential gain of mending the issues. The two issues that would have the largest gain and are in most cases, relatively easy to adjust were an inappropriate design of the

Fig. 9. Ranking of the issues based on their difficulty of implementation and commonality.

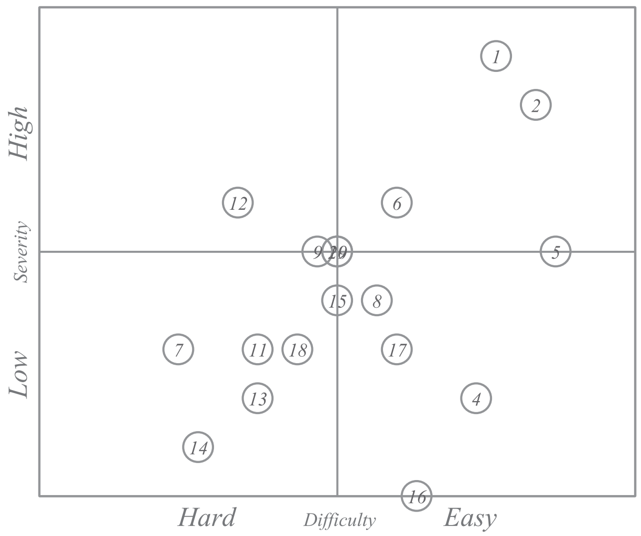

Fig. 10. Ranking of the issues based on the difficulty of implementation and their severity.

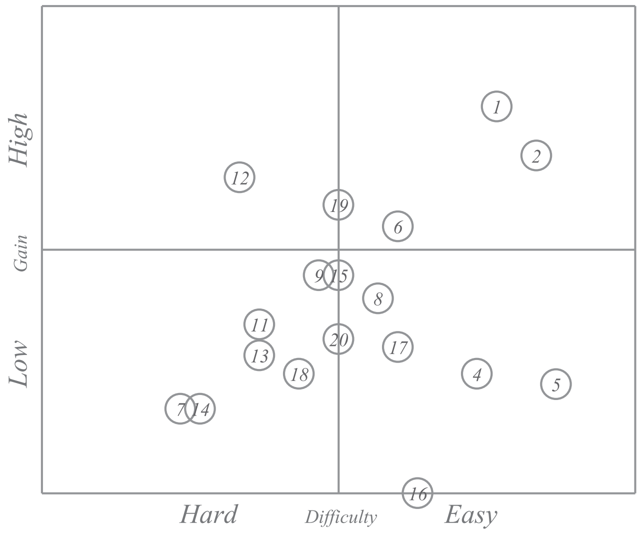

Fig. 11. Ranking of the issues based on the difficulty of implementation and possible improvement gain it has on the process.

process control and untuned process control configuration. Other issues that are more difficult to adjust, but have potentially a large impact on the process, were upstream disturbances from the preceding process, under-dimensioned units in the process and unwanted segregation caused by material handling. While on the other perspective, issues such as downstream disturbances from the subsequent process and unforeseen material hold-up or blockage in unit operation have, in most cases, a small improvement potential and are difficult to adjust. See Fig. 11. For the ranking of the issues

4. Discussions

The demand for more efficient production will only increase in the coming future. The process is affected by several different sources of disturbances during the operation. Therefore, it is important to understand it and to have a structured framework for handling the consequences of dynamic process behaviour. In this review, we have discussed how to categories different dynamics in the process of comminution and classification and how it is possible to approach these issues. How different issues and opportunities are received is dependant on subjective opinion, which is based on our previous experience. To improve the process, engineers need an arsenal of different methods and analyses to accomplish process improvements. Understanding the process and process dynamics is a critical one, and it opens up several possibilities to improve the production in multiple aspects of the operation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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