Multivariable control strategy for a bucket wheel reclaimer

Estratégia de controle multivariável de retomadora de roda de alcatruzes

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ABSTRACT
Mining operations are generally done by large machines working in very harsh environments and historically having shy embedded technology. The use of control strategies, in many cases, dramatically increases the operating efficiency without large financial investments. In this context, this paper presents the method of choice and practical application of a multivariable control strategy for a bucket wheel ore reclaimer. This strategy adopts PI and PID controllers following a type override strategy acting on the manipulated variable: the slewing angular velocity. This manipulated variable was chosen because its actions affect the controlled variable very fast, so, allowing correcting disturbances in an adequate time. In addition, a fuzzy type controller was implemented to act on a second manipulated variable: the translation step. The second manipulated variable aims at taking the first one (angular speed) out of saturation states. When working together, these controllers seek to increase the equipment and process performance, taking into account, however, their operating limitations. Finally, a statistical analysis of results was performed in order to validate the feasibility of the implanted strategy when compared with the method previously in operation.

Keywords: bucket wheel reclaimer, fuzzy control, override control, productivity.

RESUMO
As operações de mineração são geralmente feitas por grande maquinário que trabalha em ambientes severos, mas historicamente possui tecnologia embarcada tímida. O uso de estratégias de controle, em muitos casos, aumenta drasticamente a eficiência operacional sem grandes investimentos. Neste contexto, este artigo apresenta a seleção e aplicação de estratégia de controle multivariável para uma recuperadora de minério de roda de alcatruzes. Esta estratégia adota controladores PI e PID seguindo uma estratégia de sobreposição do tipo atuando sobre a variável manipulada: a velocidade angular de giro. Esta variável manipulada foi escolhida porque suas ações afetam a variável controlada muito rapidamente, permitindo, assim, corrigir distúrbios em um tempo adequado. Além disso, um controlador de lógica difusa foi implementado para atuar sobre uma segunda variável manipulada: o movimento de translação. A segunda variável manipulada procura

tirar a primeira (velocidade angular) dos estados de saturação. Ao trabalharem juntos, estes controladores procuram aumentar o desempenho do equipamento e do processo, levando em conta, entretanto, suas limitações operacionais. Finalmente, análise estatística dos resultados foi feita, a fim de validar a viabilidade da estratégia implantada, quando comparada com o método anteriormente em operação.

Palavras-chave: retomadora de roda de caçambas, retomadora de roda de alcatruzes, controle difuso, controle em cascata, produtividade.

1 INTRODUCTION

Storage and handling are activities that contribute heavily on the composition of the operating cost of the bulk materials, particularly of ore concentrates, since, as a rule, both inputs and products undergo a series of handling operations, before they reach their consumers. Handling and storage activities have been added value to place, time and quality to the supply chain. In this line, stacking and reclaiming are two correlated operations of pivotal importance in the day-to-day operations of mineral dressing plants (Luz and Peres, 1992; Castro et al., 2022).

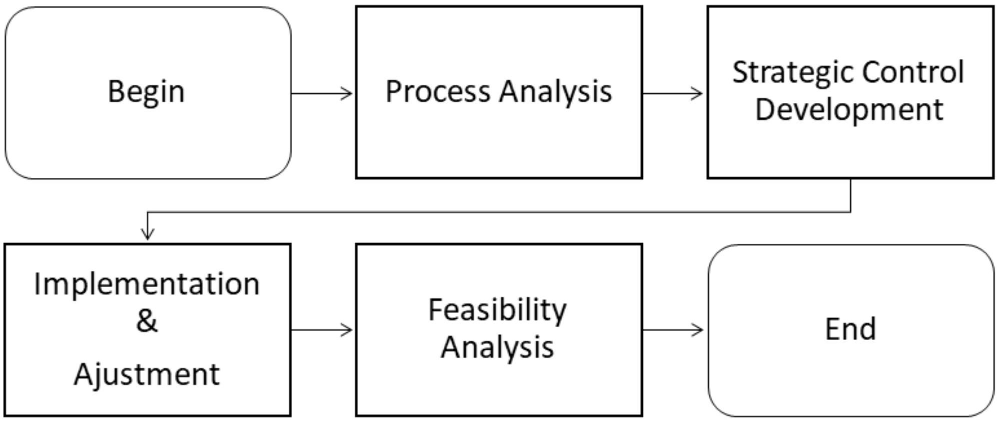
Thus, automation and control of processes become important tools to achieve this goal. As pointed out by Lu (2009), concerning the three degrees of freedom of machine movement, it can be conceived as a PRR (Prismatic–Revolute–Revolute) robotic arm.

A successful example of automation in a reclaiming operation is the one at Maasvlakte stockyard in the port of Rotterdam for coal and iron ore (iSAM AG, 2007). That system was developed by iSAM AG and is based on 3D laser scanner technology combined with a link to GPS receivers, generating a detailed terrain model in real time. There were also two sonar sensors for stockpile detection and two microwave barriers for anti-collision protection of the tilting boom. The terrain model is the basis for calculating moving commands given to the three moving axes of the stacker/reclaimer. The system allows optical generation of stockpiles and ensures a strategic reclaiming of the material.

From theoretical point of view, some studies have been reported in the literature, seeking to quantify the rate of production with the cutting pressure for granular material cutting/reclaiming. For instance, (Skonieczny and Moreland, 2011) have studied the parameters of bucket-wheel configuration for lightweight planetary excavators, adopting cohesion less granular media. As pointed out by those researchers, the classical excavation models like those ones by (McKyen, 1986), (Harold J. Luth and Robert D. Wismer, 1971) and (Balovnev, 1983) suggests wide buckets are highly productive, especially for continuous excavators, which do not suffer from increased resistance from soil accumulation, since a new empty bucket is repeatedly introduced to cut the granular medium. Excavation resistance is shown to depend mostly on the ratio of bucket-wheel rotation rate to forward advance rate.

In this context, this study aimed to design, deploy, and statistically analyze the performance of a specific control strategy for an iron ore (sinter feed) reclaimer, with respect to reclaiming flow rate, occurrence of overshooting and equipment capacities. The flowchart shown in the Figure 1, represents the steps that were taken to get this work done.

Figure 1 — Process Optimization Flowchart



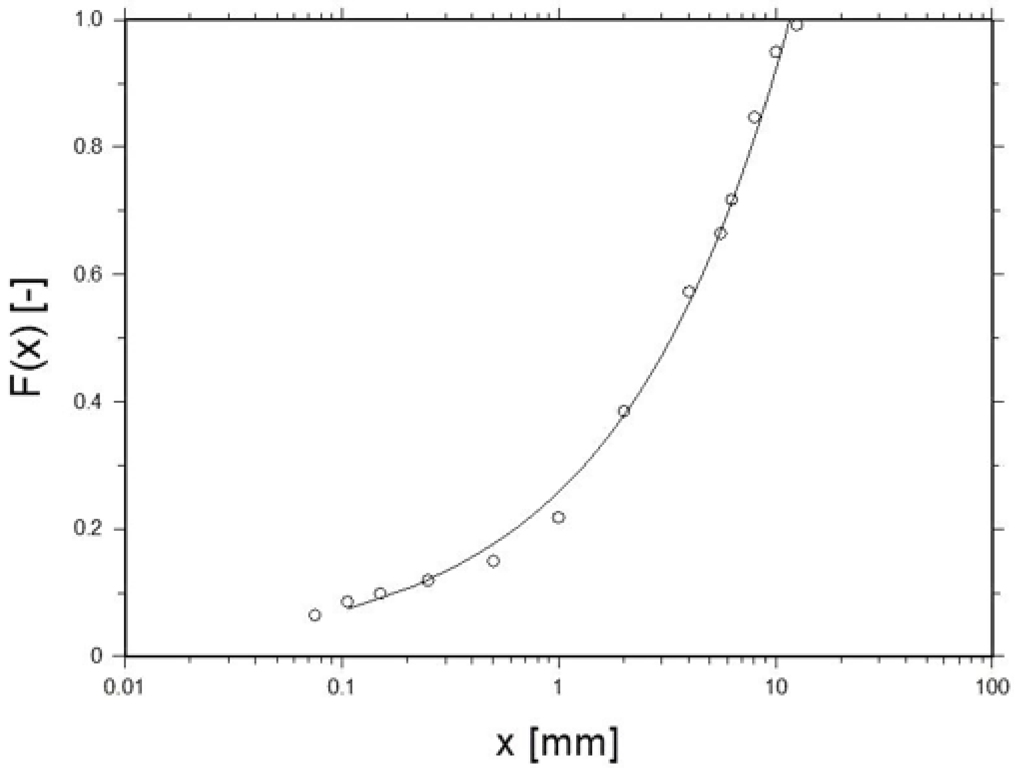
2 BULK MATERIAL FEATURES

Handling of bulk or granular materials is an ancillary operation in processing of ores and other particulate materials. As a matter of fact, they are very complex in their rheological behavior (Forterre and Pouliquen, 2008; Luz and Silva, 2005; Silva and Luz, 2004). With regard to the granular material studied in this work, the following table (Table 1) systematizes their main physical properties. The Figure 2 display particle-size distribution of this material ($\boldsymbol{Y} = \boldsymbol{F(x)}$, as cumulative fraction passing through the sieve openings, $\boldsymbol{x}$). The solid curve is the regression Gates–Gaudin–Schumann equation, which has showed good statistical adherence (coefficient of determination $\boldsymbol{R}^2 = 0.9951$).

Table 1 — Average characteristics of the sinter feed reclaimed

Material	Iron ore sinter feed
Average moisture	12.0 %
Solid actual density	4,700 kg/m³
Bulk density	2,600 kg/m³
Bed (interstitial) porosity	44.7 %
Dynamic angle of repose	26º @ 38º
Surcharge angle on belt conveyor	8 º @ 15 º
Nominal minimum particle size	0.00015 m
Nominal maximum particle size	0.00953 m

Figure 2 — Particle size distribution of sinter feed



The regression analysis was performed employing *EasyPlot*© software. The resulting Gates–Gaudin–Schumann distribution is:

$$Y = F(0 \leq x \leq x_{\max}) = \left(\frac{x}{x_{\max}}\right)^{a} = \left(\frac{x}{11.6\ \text{mm}}\right)^{0.552} \qquad (1)$$

3 RECLAIMING PROCESS

In the first stage of this work, reclaimer characteristics and the routine required for its operation were analyzed in order to select monitoring and control variables. In this context, a historical database of equipment variables (belonging to an iron ore mining company located in the state of Minas Gerais, Brazil) was debugged in order to eliminate possible outliers.

The reclaimer is a cell-less bucket wheel type; and it has a block retrieving system. Its main features are described below (Table 2).

Table 2 — Characteristics of bucket wheel reclaimer

Design reclaiming capacity (metric tons per hour):	5,800 t/h
Nominal reclaiming capacity (metric tons per hour):	4,000 t/h
Boom length:	35 m
Rail gauge:	8.5 m
Total weight (including 150 tons of counterweight):	540 tons (in operation)
Maximum tilting angle:	+ 8 degrees
Minimum tilting angle:	- 15 degrees
Maximum turning angle (slew):	330 degrees
Operation travel distance:	250 m
Cutting circle diameter:	7.5 m
Traveling velocity (no-load operation):	0.50 m/s
Traveling velocity (full-load operation):	0.25 m/s
Number of scooping buckets:	8
Angular velocity of the reclaimer's wheel:	0.628 rad/s (6.0 rpm)
Cutting velocity:	2.36 m/s
Theoretical throughput of reclaimer wheel:	8 · 6.0/60.0 = 0.80 bucket/s
Bucket volume:	0.8 m³
Theoretical throughput of reclaimer:	0.80 x 0.8 x 3,600 = 2,304 m³/h
Tilting velocity of boom tip:	0.0378 m/s

The Geometrical aspect of each bucket is showed in Figure 3. At right a theoretical curve is shown obtained in order to check the nominal bucket volume. The curved profile can be described by the following equation normalized by the dimension $\boldsymbol{w}$ = 0.830 m (showed in Figure 3):

$$y_n = \frac{y}{w} = 1.35 \times \left\{ 1 - \left[1 - \left(\frac{x}{w} \right)^{1.55} \right]^{0.4545} \right\} \tag{2}$$

Figure 3 — Normalized bucket profile (maximum abscissa is the bucket side opening: ***w*** = 0.830 m)

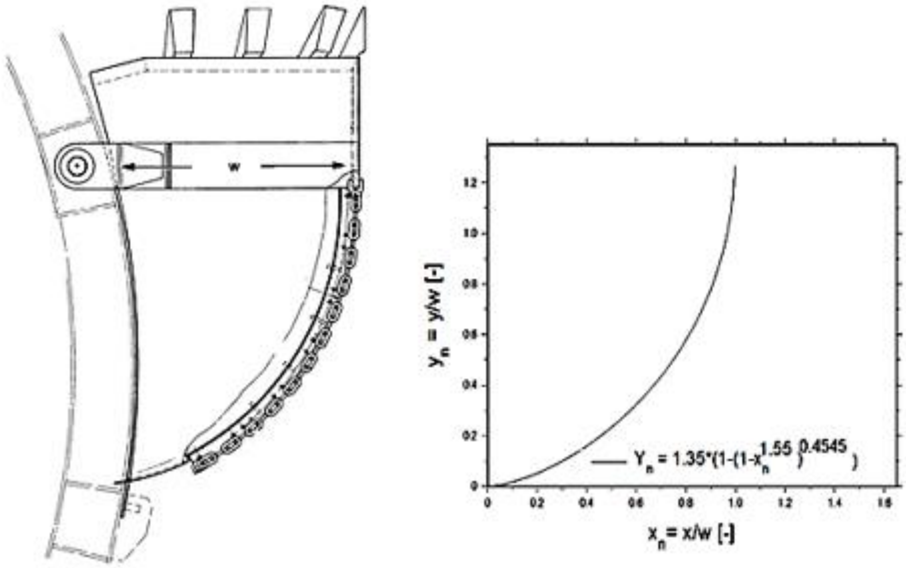
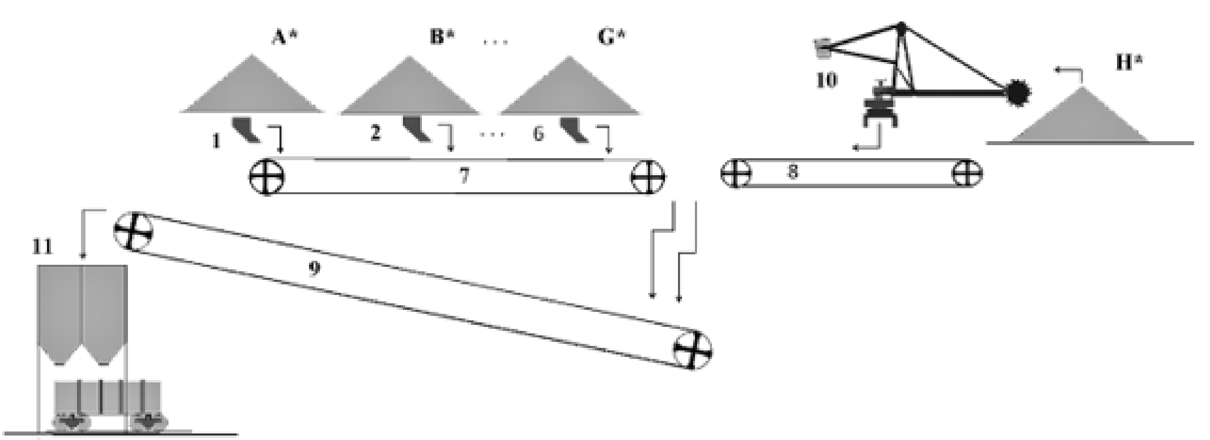


Figure 4 illustrates schematically the handling process route that includes the reclaimer in which was implemented the control strategy described herein.

Figure 4 — Conceptual flowsheet of granular media handling and storage. Legend: ***A****, ***B****, ***…***, ***H****: stockpiles (stacks ***C****, ***D****, ***E****, and ***F**** are not shown); ***1***, ***2***, ***…***, ***6***: ore hoper (hopers ***3***, ***4***, and ***5*** are not shown); ***7***, ***8***, ***9***: belt conveyor; ***10***: bucket wheel reclaimer; ***11***: surge bin



In stockyard under analysis there are eight stockpiles (***A****, ***B****, ***C****, ***D****, ***E****, ***F****, ***G**** and ***H****), with various particle size ranges and iron content, in short represented in Figure 4. The stockpiles to be reclaimed in this stockyard are stacked using cone-shell and chevron methods. Often, these stockpiles get into reclaiming even before the completion of their stacking process. This point is important since process conditions may change significantly.

For stockpile gravity reclaiming there are several mass flow hoppers located at the bottom of six stockpiles that can feed the belt conveyor ***7*** in a relatively constant flow rate. The hoppers work independently from the bucket wheel reclaimer, that is, the surge bin loading can be done alternatively either only by reclaim hoppers or by the bucket wheel reclaimer only or both simultaneously.

The bucket wheel reclaimer ***10*** has boom of 35 m long. The bucket wheel angular velocity is constant and equal to 0.628 rad/s (6 rpm). This equipment has a nominal mass flow rate capacity of 4,000 t/h (average expected target) and 5,800 t/h is the maximum capacity (USL — upper specification limit). The reclaimer can travel over the whole stockyard, enabling reclaim of all eight stockpiles available there.

The belt conveyors showed in Figure 4 shall transport the reclaimed material to the surge bin ***11***. Belt conveyor ***9*** is a bottleneck in the process, since it has no ability to simultaneously transport the ore received from the belt conveyors ***7*** and ***8*** when the two are conveying ore at their nominal capacities.

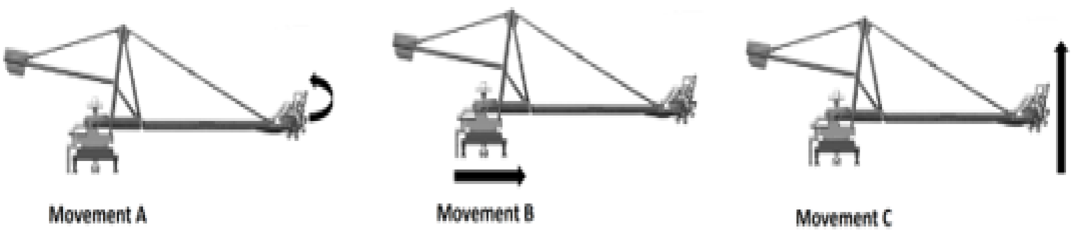
The surge bin stores the material from belt conveyor ***9*** until the operator opens its bottom gates, eventually loading the railcars.

With regard to reclaimer operating cycle, Figure 5 visually describes its degrees of freedom and the reclaiming process. Such movements are:

1. Raise or lower the boom at the desired operating height. (Motion ***C*** — Figure 5);
2. Slew or turn the bucket wheel against the stack, starting the reclaimed process (Movement ***A*** — Figure 5);
3. After each boom slewing cycle, the reclaimer should be approximated across the stack, in order to perform one more rotation (Movement ***B*** — Figure 5);
4. Repeat steps 2 and 3.

These steps should be followed until the pile is over (fully reclaimed) or until the silo loading operation is finished.

Figure 5 — Movements of the reclaim cycle (A: slewing or rotation; B: rail travel; C: ascent and descent)



As pointed out by Hinrichsen, Haye (2004), there is both a scientific and a technological challenge to develop a phenomenological understanding of the underlying the flow of grains. In fact, this is a very complex issue. So, the approach use here has taken into account only operational factors.

3.1 PROCESS VARIABLES

- ***Angular velocity of the boom (slewing motion)***.

The rotation angular velocity or slewing velocity is given by **Erro! Fonte de referência não encontrada.**:

$$w = \frac{\Delta\theta}{\Delta t} \tag{3}$$

Where: $\boldsymbol{w}$ — rotation angular velocity or slewing velocity [rad/s]; $\boldsymbol{\Delta\theta}$ — angle variation [rad]; $\boldsymbol{\Delta t}$ — time interval [s]. The rotation angular velocity directly influences the reclaiming flow rate. For this reason, it was included as manipulated variable in the control loop designed.

- ***Translation movement step***

The step of travel movement on the rail was one of the variables to be manipulated by the proposed control system. This step is defined as the reclaimer's approach movement, per turning in the reclaiming cycle. A suitable step size is critical to the proposed control and, consequently, for achieving their desired results. This is important, since this may lead the slew actuator to work close to the saturation limits (0 % or 100 %). Working under these conditions may prevent the process variable to stay close to the setpoint, making the control inadequate.

- ***Mass flow rate***

The mass flow rate reached by the reclaimer is the main process variable.

- ***Working Pressure***

The bucket wheel of the equipment has a hydraulic drive. The process variable of the controller is given by the readings of hydraulic pump transmitter of working pressure for the excavation work. This variable is important since it could give an idea about how much ore is being reclaimed before it’s been measured by the instrumentation.

- ***Belt conveyor 9 — motor current***

The motor current from belt conveyor ***9*** is a key variable since an overload in this motor could cause many operational troubles like having to unload the belt manually consequently affecting the operational performance.

Once studied the reclaimer work cycle, its process variables were analyzed, covering parameters such as working pressure of the bucket wheel, turning angle, angular velocity of boom, reclaimer positioning in the stockyard, translation step size and reclaimer flow rate. Data were collected during several shifts operating at one second intervals.

3.2 STATISTICAL ANALYSES

The analysis of these data has allowed investigating the equipment and methodology limitations and operation thereof, serving as a reference for the control strategy. In addition, there was a brief study about the side processes concerning to reclaiming. This study was of paramount importance to improve applicability and effectiveness of the proposed control strategy.

The data analysis has consisted of statistical methods to look for correlations and trends of process variables, according to the usual techniques of time series analysis.

After analyzing the reclaiming process, a control strategy was proposed.

4 CONTROL STRATEGY

In order to get a good control strategy, firstly, the objectives of the control mesh should be set. These objectives should be based on knowledge, expected results, requirements and limitations of the process to be controlled, besides the professional skill of those who are designing the control strategy. This main objective, as set before, needs to get a reclaimer productivity improvement (greater amount of reclaimed ore in less time) meeting all process constraints.

According to Seborg (2009), once defined the control objectives, the definition of the strategy can be carried out in four steps as follows.

4.1 DIVIDING THE CONTROL PROBLEM INTO SMALLER PROBLEMS

The process of storage and handling is a process with many variables and equipment. As a matter of fact, the control problem has been previously divided into smaller parts, delimiting therefore the scope of the search for a control strategy to the bucket wheel reclaimer and some adjacent equipment, thus making the focus of this work.

Despite the goal of this controller is to increase the reclaimer productivity, it is important to always observe some requirements such as personal safety and assets involved, environment, productivity, economic factors of development, stability of the production process.

The Table 1 shows the process variables to be handled by the controller and also its maximums values.

Table 1 — Process Variables

Process Variables	Description	Maximum Value Expected
PV1	Instantaneous flow rate of reclaimed ore	5,800 t/h
PV2	Working pressure	200 bars
PV3	Electrical motor current for belt conveyor ***9***	75 A

Since the maximum value expected (USL — upper specification limit, showed in Table 1) are the permissible values for that equipment, the main objective of the proposed control was to increase the average mass flow rate of handling under such limitations.

4.2 CHOOSING THE VARIABLES TO BE MANIPULATED

The reclaimer in operation has three degrees of freedom, as showed in Figure 5. Therefore, there are three variables that can be manipulated during the reclaiming process: the boom's slewing speed, the magnitude of the translational movement step and the elevation or height. The height should stick to fixed positions due to operational constraints, so in case under analysis only angular velocity of boom rotation and rail travel step were taken as variables to be manipulated (Table 1).

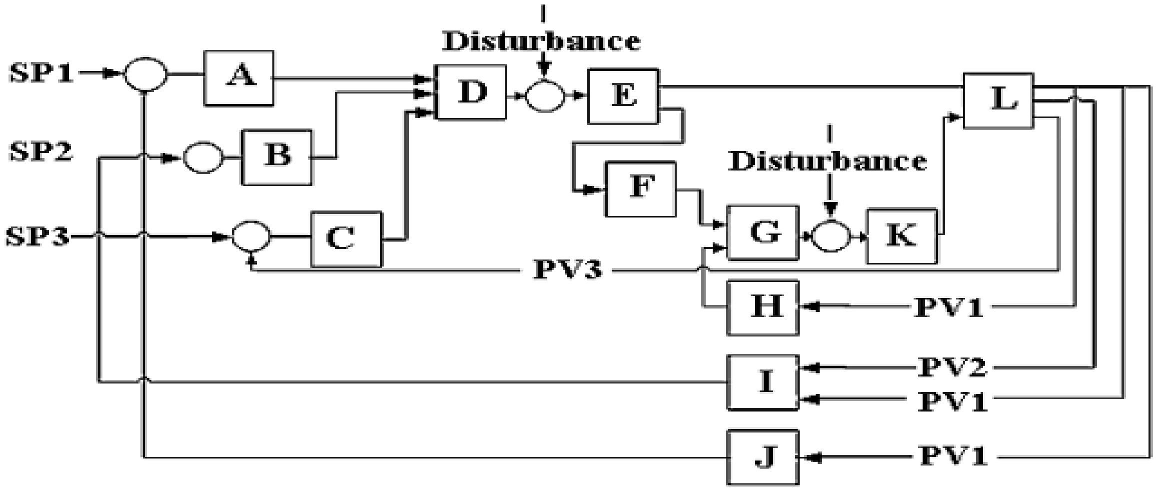
Table 2 — Manipulated Variables

Manipulated Variables	Description
MV1	Slewing velocity
MV2	Rail travel step

4.3 CHOOSING THE TOPOLOGY OF THE CONTROL LOOP

A decentralized control structure was elected to this task in search of greater flexibility, that is, one strategy for each manipulated variable. A conceptual control diagram for the designed configuration is displayed in Figure . The proposed control consists of two distinct strategies to control the manipulated variables: bucket wheel angular velocity and rail travel step.

Figure 6 — Control strategy diagram. Legend: ***A***: controller 1; ***B***: controller 2; ***C***: controller 3; ***D***: selector; ***E***: spin drive; ***F***: calculus 1; ***G***: controller 4; ***H***: calculus 2; ***I***: calculus 3; ***J***: calculus 4; ***K***: travelling drive; ***L***: process



4.3.1 Override Control

An override control was adopted for boom turning movement or slew. The idea of this strategy is to get a rotating angular velocity which results in the greatest average mass flow rate, taking into account the process limitations. For this purpose, three different controllers were used, each working distinctly in each of the previously defined process variables (operating pressure, mass flow rate and electrical current in belt 9), and a selector algorithm defines which of these three controllers will assume the control of the manipulated variable (angular velocity of rotation).

- ***Controller 1***

The purpose of the ***controller 1*** is to keep the average reclaiming mass flow rate around the setpoint. A PID controller type has been chosen for this task, with the following characteristics:

- ***Setpoint (SP1):***

The reference value is the average mass flow rate of 4,000 t/h, as this is the nominal capacity of the reclaimer.

- ***Process Variable (Calculus 4)*****:**

The average of instantaneous mass flow rate was used as process variable. In order to get this average, the mass that was on the belt at every moment (material inventory) was calculated. This calculation had to be carried out because the instrumentation system only gets the instant flowrate.

The reclaimer belt conveyor has 35 m long and operates at an average speed of 3.77 m/s. Therefore, the reclaimed material stays on the belt for 9.28 seconds. The rounded figure of 10.00 s was adopted in order to simplify calculus.

The actual value of the process variable (average mass flow rate) of the ***controller 1*** is calculated based on 5 s after the scale. It was defined in that way because the material stays on the belt for 10.0 seconds and during the first 5.0 s seconds is not possible to get its mass flow rate in real time (due the place where the instrumentation is placed). The calculus 4 is given by Equation 4:

$$Calculus\ 4 = \frac{PV1_{n-4} + PV1_{n-3} + PV1_{n-3} + PV1_{n-2} + PV1_{n-1} + PV1_{n}}{5}; \forall n > 4 \qquad (4)$$

Where: ***Calculus* 4** — process variable (average mass flow rate) [t/s];

$\boldsymbol{PV1_n}$ — mass flow rate at instant $\boldsymbol{n}$ [t/s].

- ***Controller 2***

The ***controller 2*** is intended to avoid the flow rate peaks in equipment (instantaneous rates above 5,800.0 t/h). In addition, it prevents overloads in the bucket wheel, keeping the working pressure below 200 bars. In other words, this controller has protection function in case of instantaneous flow rate surge or abnormal operating pressure. For such aim, a PID control action was taken under the following characteristics:

- ***Setpoint (SP2 or Calculus 3)*:**

The control of the instantaneous flow rate was set to be done by the relationship between the reclaimer flow rate and the working pressure. This choice was due to the great distance between the granular material cutting point by the bucket wheel and integrator scale, making it impossible to control the instantaneous flow rate from scale readings.

In view of the theoretical complexity of granular systems phenomena, an empirical approach was attempted. A positive correlation between of reclaimed flow rate and pressure in the bucket wheel is noticeable. The Pearson's method was used to demonstrate this correlation (Pearson, 1900). Despite the variance of measurement and data acquisition with stochastic character, one can accept as strong the relationship between the working pressure and mass flow rate reclaimed. Initially, a linear relationship between these two variables was adopted. The instantaneous working pressure (***P***) is given by Equation 5:

$$P = a * V + b \qquad (4)$$

The values of coefficients ***a*** and ***b*** depend on several factors such as ambient, temperature, equipment maintenance conditions (mechanical component gripping, clearances, scale calibration), and others, making it impossible to have reliable constant values over time. In this sense, it is important to have these values being updated dynamically, in order to well portray the relationship between the variables during the moment of inference, making the control more robust. The following procedure was developed in order to calculate these coefficients.

- ***Linear coefficient or intercept (b):***

Naturally, from Equation 5 this parameter is given by the expression Equation 6:

$$b = P - a * V \qquad (5)$$

The value of the intercept (expressed in bars) can be defined by work pressure in occasions when both flow rate readings from scale and slewing velocity of the boom are zero in the last 10.0 seconds, although the bucket wheel is in operation. Accordingly, one can define the value of this linear coefficient, since flow rate, ***V***, in this situation is zero. Therefore, the following expression holds:

$$b_n = P_n \qquad (6)$$

Where: $\boldsymbol{b_n}$ — linear coefficient at moment ***n*** [bar]; $\boldsymbol{P_n}$ — instantaneous working pressures at moment ***n*** [bar]. The intercept ***b*** is calculated from the moving average of the last 5.0 s of pressure measures, in order to minimize impacts due to spurious instantaneous measurements. Therefore, to ***b*** is now defined by:

$$b = \frac{P_{n-4} + P_{n-3} + P_{n-2} + P_{n-1} + P_n}{5};\ \forall n > 4 \qquad (7)$$

Where: $\boldsymbol{P_{n-}}$ — instantaneous working pressure at moment ***n***, while the reclaimer stays running idly ($\boldsymbol{V_n} = 0$).

- *Angular coefficient (**a**):*

As discussed previously, the values given by the scale are delayed about 5.0 seconds after the material is taken up by the bucket wheel. In this regard, the calculation of the slope is given by:

(8)

$$a_n = \frac{P_{n-4} - b}{v_n}; \forall n > 4$$

Where: $\boldsymbol{a_n}$ — angular coefficient [bar.s/ton]; $\boldsymbol{v_n}$ — instantaneous mas flow rate from scale readings at moment $\boldsymbol{n}$ [m/s].

Similarly, to the case of the intercept, the angular coefficient is calculated from the moving average of the last 5 seconds, aiming to minimize impacts due to inconsistent and instantaneous measurements and adopted approximations. It is thus calculated as:

(9)

$$a = \frac{\frac{P_{n-8} - b}{v_{n-4}} + \frac{P_{n-7} - b}{v_{n-3}} + \frac{P_{n-6} - b}{v_{n-2}} + \frac{P_{n-5} - b}{v_{n-1}} + \frac{P_{n-4} - b}{v_n}}{5}; \forall n > 8$$

Once the values of intercept and slope having been estimated, the instantaneous flow rate can be inferred by:

(10)

$$V = \frac{P - b}{a}$$

The maximum instantaneous flow rate for this equipment is 5,800 t/h. This controller has protection function so the setpoint of flow rate must be below this value. The setpoint initially selected was 4,640 t/h. Thereby, the controller has the freedom to act with overshooting of up to 25 % without exceeding the equipment maximum value.

In this way, the setpoint for the working pressure, respecting the mass flow restriction, can be given by Equation 12:

(11)

$$SP_A = 4640a + b$$

The setpoint for protecting the working pressure is: $\boldsymbol{SP_B}$ = 190 bars. The smaller freedom is justified by low operational impact if the operating pressure reaches 200 bars, which is offset by the productivity gains generated by working as close to the upper limit of the equipment.

Therefore, in order to meet two constraints, the following algorithm explicated by Equation 13 (*Calculus 3* block from Figure 6 — Control strategy diagram), was adopted for the ***controller 2***:

(12)

$$SP2 = \begin{cases} 0; se\ SP_A < 0 \\ SP_B; se\ 0 \leq SP_A \leq 190 \\ 190; se\ SP_A > 190 \end{cases}$$

➢ ***Process Variable (PV2):***

The process variable of the controller is given by the readings of hydraulic pump transmitter of working pressure for the bucket wheel excavation work.

➢ ***Controller*** **3**

The ***controller 3*** is intended to keep the conveyor ***9*** electrical current below its nominal current, preventing overloads and circuit shutdowns. Control action of type proportional-integral (PI) was adopted for this controller (Woolf et al., 2022). The derivative variable component was not adopted due to the long response time of the controlled variable. Therefore, one has:

➢ **Setpoint *(SP3):***

It was defined the current value of ***SP3*** equal to 68.18 A, allowing freedom of approximately 10 % for the possible occurrence of overshooting.

➢ ***Process variable (PV3)***:

The belt conveyor ***9*** has two electric motors on its drive. Thus, this process variable is given by the value measured by the motor with higher instantaneous electrical current. This choice is made in order to treating the worst case, since the controller 3 aims to protect the equipment.

➢ ***Selector***:

The selection of which of the three controllers effectively sends the command to the manipulated variable was made from comparing which of the three controllers have the lowest absolute value calculated for the manipulated variable (turning velocity of the boom). The choice of lower value means meet the worst case, that is, meet all the aforementioned operational limitations of the equipment.

An important point to note is that the boom turning motion constantly suffers manual intervention. These interventions should be considered for operational safety reasons. Thus, the operator's experience also influences the behavior of the process variable (mass flow rate). In the Figure these interferences are represented as disturb.

4.3.2 Fuzzy algorithm control or Controller 4

A fuzzy logic-based algorithm has been proposed to determine the step size of the reclaimer translatory motion. The choice of this type of control was due to the fact that fuzzy controllers are suitable for cases of non-linearity of the system. In addition, fuzzy control has good flexibility to process changes and ease of implementation.

The goal of ***controller 4*** had been to get a step value that avoid large overruns in the turning control (speed at the maximum or minimum values) and expected reclaiming flow rates. In this context, the control sought to adjust the step size to the turn speed values and mass flow rate reclaimed during the last preceding turning cycle. A fuzzy controller was implemented for this, and the input variables are the average turning speed and maximum mass flow rate of the last turning cycle.

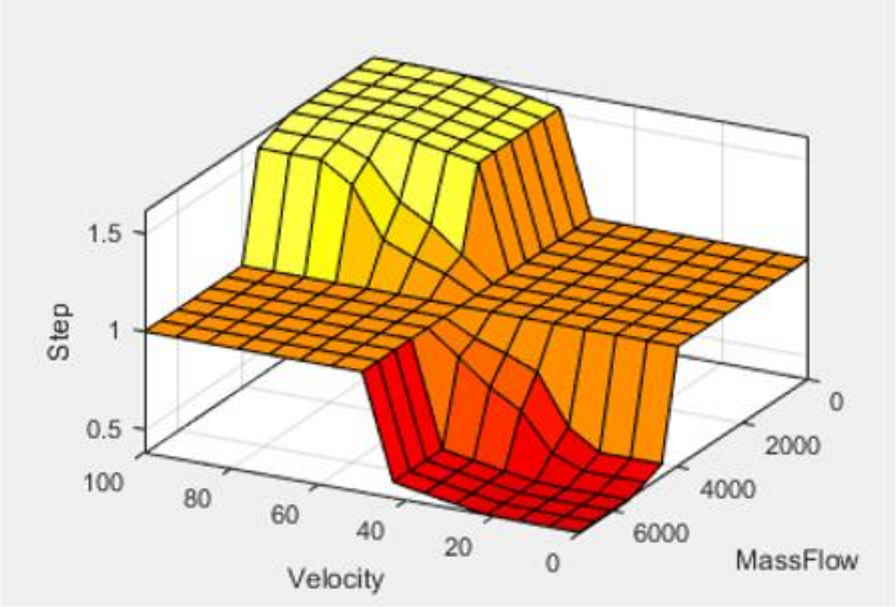
The reference ranges for fuzzification were defined from the nominal capacity of bucket wheel equipment and minimum and maximum allowable turning velocity.

Once having the fuzzified input variables, these have been applied in the fuzzy controller inference rules. These rules were determined from knowledge of the process to be controlled and are presented below:

- IF Velocity = Low AND mass flow rate = High THEN step = Small;
- IF Velocity = Medium AND mass flow rate = Medium THEN step = Medium;
- IF Velocity = High AND mass flow rate = Low THEN step = Big.

After defined the key parameters of fuzzy controller, the output variable behavior (step) was observed in function of the input variables (turning or rotating speed and mass flow rate) through simulations in software. These simulations were performed to prevent step values that were incompatible with the reality of the process. Figure 6 graphically represents the behavior of the driver in relation to the input variables.

Figure 6 — A behavior of the variable "step" as a function of two entries: boom angular velocity and scale readings



4.4 MAKING ADJUSTMENTS OF CONTROLLERS' PARAMETERS

The initial values for adjustment of the adopted controllers were defined. Then the proportional gains, the integral gains of ***controllers 1***, ***2*** and ***3***, as well as the fuzzification and defuzzification attributes for ***controller 4*** were determined.

It is important to stress that these values were accepted as initial ones only. There was an expectance of the future need to do a fine tuning in order to reach the best values for the algorithm parameters, in case of unsatisfactory results after the controlling system implementation.

5 FEASIBILITY ANALYSIS

Once the new controlling system has been commissioned in industrial scale, a comparison between the performance before and after the controlling system deployment was carried out.

This comparison aimed at to detect the expected impact from the new strategy of control. In order to reach that, three selected time series of full-scale operational data, while the new controlling system was switched off, were compared with other similar three selected full-scale sets of operational data with the new controlling systems in complete operation.

In order to get more homogeneity of data and to reduce the influence of some process variables which could influence the performance results, the choice of data samples has observed the following criteria:

- The period analyzed duration should be equal (3,600 s);
- The ores to be reclaimed should have similar properties (they had about the same particle size distribution and same bulk density);
- The stockpile formation method should be similar (chevron type stacking in all cases);
- The samples should come from periods of steady state operation, it is, the reclaimer should be running after any maneuvers and initial positioning and there was no change of the reclaimed pile.

The developed strategy was implemented on an industrial scale with calibration of algorithmic parameters of controllers. Finally, a statistical study was conducted in order to evaluate the applicability of the proposed control loop and analyze their impact on the process. This statistical analysis of the data collected (previously treated in order to rule out spurious data) was performed with employment *Minitab* software package, version 16.

According to these rules, three samples (samples 1, 2 and 3) were collected while the new controlling system was switched off, and three counterpart samples (samples 4, 5 and 6) while the new system was switched on.

Subsequently, it was checked if the new strategy of control had met the prevailing process constraints. For this purpose, the frequency of occurrence of the overloading of belt conveyor ***9***, excessive working pressure in bucket wheel motorization and reclaiming mass flow rate above the equipment capacity were investigated. In these questions all parameters it has fallen within the expected range (no negative impact on equipment).
In view of this, the average reclaimed rate of granular material was analyzed. These average flow rates obtained in handling operation before and after the implementation of the controlling system can be seen in Table 3.

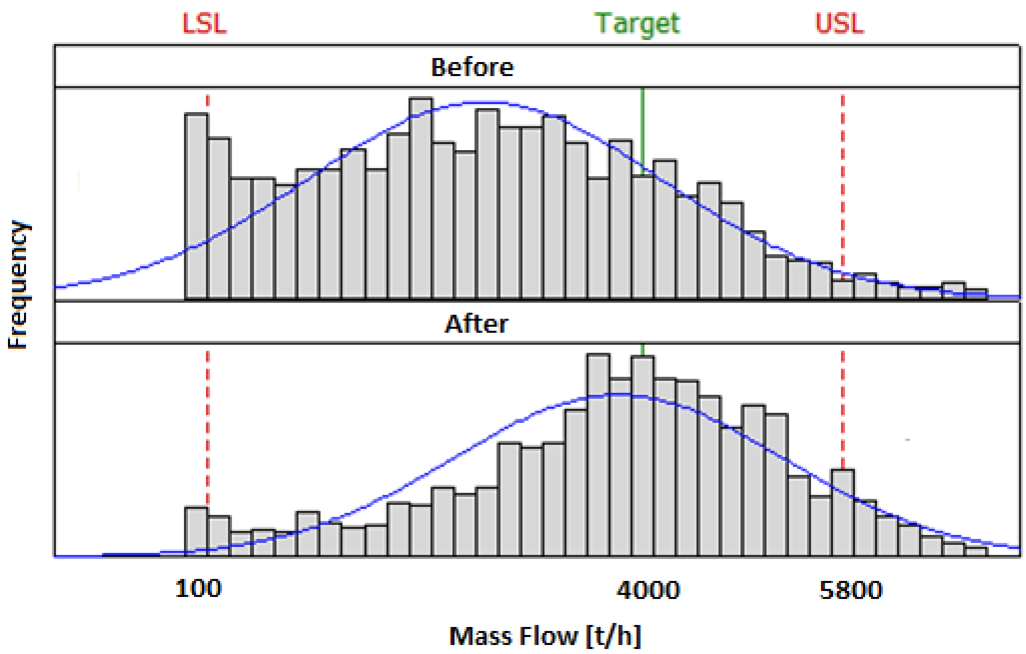
Table 3 — Effect of new strategy of control on reclaimer's mass flow rate.

average flow rates (t/h)	New controlling system switched off			New controlling system switched on		
	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
	2,390.8	2,659.2	2,684.3	3,975.3	3,583.4	3,776.0

According to the results shown in Table 3, the bucket wheel reclaimer had worked previously significantly below their nominal capacity (4,000 t/h), creating the opportunity for optimization. Figure 7 illustrates graphically the positive impact of the implementation of the new control system in full scale.

The new control strategy proved to be beneficial for the proposed application. This strategy has managed to meet the operational requirements of the control, in addition to increasing the operational performance of the equipment, leading the average flow rate during reclaiming operation in stockyard from 2,579.5 t/h, before implementation of the proposed controlling system, to 3,781.6 t/h, after of said system activation. An improvement of performance of 46.6 % was obtained. The new control strategy, therefore, besides contributes to the increase of productivity of the reclaimer and consequently the whole rail logistics chair since the loading times of the wagons suffered a strong reduction. In this context, the proposed control strategy can serve as a reference for other work in the area of optimization of granular material handling processes.

Figure 7 — Histogram comparison between control strategies



6 CONCLUSION

Unlike most studies in the literature, this study sought to create a control strategy for a non-fully automated process, that is, the manipulated variables can suffer all the time interference from reclaimer operator. The controlling system had developed and implemented as a requirement to be robust enough to suit these frequent human interventions and overcome possible failures of the installed instrumentation.

A comparative study was carried out, and eventually has validated the positive impact on the operation reached by the new strategy implemented when compared with previously strategy. It was possible to assess the increase in the average mass flow rate without increase of overshooting frequency. There was a significant improvement over 46.6 % in average flow rate, so that the proposed control strategy proved entirely feasible.

The strategy developed, despite being specific to this case study, may be adapted to various reclaimers for granular media or other similar systems, which demonstrates the broad scope of this approach. As ergonomic aspect is concerned, some further improvements in the control system were not implemented because preliminary experiments showed that this would result in somewhat abrupt changes in the cockpit positioning, even causing discomfort to the operator (sea sickness).

In this sense, the authors think that this work has helped to demonstrate the practical applicability of the simple control strategies on the performance improvements of processes and, consequently, of operating results in multimillion-dollar equipment like ore reclaimers.

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