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Centralized Finite State Machine Control to Increase the Production Rate in a Crusher Circuit

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Abstract: Crushing is a critical operation in mineral processing, and its efficient performance is vital for minimizing energy consumption, maximizing productivity, and maintaining product quality. However, due to variations in feed material characteristics and safety constraints, achieving the intended circuit performance can be challenging. In this study, a centralized control strategy based on a finite state machine (FSM) is developed to improve the operations of an iron ore crushing circuit. The aim is to increase productivity by manipulating the closed-side-setting (CSS) of cone crushers and the speed of an apron feeder while considering intermediate storage silo levels and cone crusher power limits, as well as product quality. A dynamic simulation was conducted to compare the proposed control strategy with the usual practice of setting CSS to a constant value. Four scenarios were analyzed based on variations in bond work index (BWI) and particle size distribution. The simulation results demonstrate that the proposed control strategy increased average productivity by 6.88% and 48.77% when compared to the operation with a constant CSS of 38 mm and 41 mm, respectively. The proposed strategy resulted in smoother oscillation without interlocking, and it maintained constant flow rates. This ultimately improved circuit reliability and predictability, leading to reduced maintenance costs.

Keywords: crushing circuit; iron ore; multivariable control; process control; finite state machine

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1. Introduction

Crushing circuits—comprising storage silos, conveyor belts, screens, feeders, and crushers—are responsible for reducing the particle size of rocks to either become a final product (observed in the aggregates industry and in some mineral processing plants) or to prepare it for further processing in grinding and flotation circuits (observed in most mineral processing plants). The control problem of a crushing circuit is not trivial due to long time delays and nonlinearities from the plant and the effect of unmeasured disturbances from upstream stages [1,2]. The importance of the crushing circuit, from both the industrial and academic perspectives, is evident from the number of publications addressing one or multiple issues of its proper operation [3]. For example, Refs. [4–7] focused on the modeling and control of the cone crusher, while Refs. [8,9] developed discrete element method (DEM)-based simulations to better understand the first principles behind the comminution stages in the cone crusher. Ref. [10] showed how the layout of a crushing plant influences the circuit performance from a qualitative perspective, and [11–18] proposed different control strategies to optimize various operating aspects of the crushing circuit.

Among the many proposed control approaches, strategies based on expert systems stand out, since in general, these strategies are not computationally demanding and are simple for plant operators to understand and accept [19]. In this sense, Ref. [14] presented a control approach for a crushing circuit based on an expert system for the plant start-up phase, throughput setpoint change, and operation under power constraint cases. The strategy is compared to a proportional–integral–derivative (PID) control strategy in which the speeds of the feeder and conveyor belts in the crushing circuit are adjusted to control recirculating flowrates, power consumption in the crusher and feed chamber hold-up in the crusher. Experimental results showed that the expert system could drive the throughput to its setpoint faster than could the PID strategy, both in plant start-up and throughput setpoint change scenarios. For a crushing circuit in a copper plant, Ref. [19] implemented an expert system to increase throughput, reduce variability, and reduce plant stops. The main manipulated variable was the feeder speed in the secondary and tertiary crushing circuits. To evaluate the proposed control strategy, the amount of material processed in the plant and the number of plant stops were measured during operation in manual mode and with the expert system. The expert system increased the circuit processing capacity by 2.1% and decreased the number of plant stops by 55%. In contrast, Ref. [1] proposed a hierarchical control strategy for crushing circuits. The outer control strategy considers the mass balance of the crushing circuit, modeled as a single storage unit, allowing for maximum utilization of the circuit capacity by maximizing the feed rate. The simplified outer model is an integrating transfer function with time delay and ignores the complex interactions and nonlinearities of the crushing plant. The inner control loops, comprising mass flow and level control loops, are responsible for guaranteeing equipment integrity. The control strategy was tested in an aggregates plant, resulting in stable operation and fast rejection of disturbances in the feed rate. In the same vein, Ref. [16] reported the implementation of a hierarchical control structure in a crushing circuit. The basic layer consists of PID and interlock sequences to guarantee that the plant operates within safety levels and to enforce the setpoints provided by the upper control layers. A supervisor layer based on a 75-rule fuzzy expert system allows for decoupling nonlinear process variables. Finally, an optimizing MPC layer tries to minimize the specific energy consumption of the plant, guaranteeing that the throughput is kept above its minimum threshold. Other goals of the control strategy are to calculate optimal bin levels to reduce plant interlocks, enforce the maximum utilization of the capacity of the plant, and address the effect of disturbances in the feed properties. The authors reported that the MPC strategy is responsible for an increase of 9% in plant throughput but reinforced that the improvement would not be achieved without effective base control layers.

Alternatively, Ref. [17] implemented an FSM in an aggregate crushing circuit. The CSS of the crusher is adjusted based on the performance of the crushing circuit, measured in terms of product throughput. The algorithm has a momentum term, in which past derivatives of the performance with respect to the CSS are also considered in the CSS control rule. The crusher operating at the plant is an Allis Chalmers 36″ Hydrocone equipped with a controller, called ASRc, that increases the CSS if the hydraulic pressure in the crushing chamber is too high. The proposed algorithm was compared to a fixed CSS in 45 min intervals over 3 months of operation. The authors reported a 3.5% increase in the performance at a 3% significance level and argued that the particular circuit has a high reduction ratio; thus, the ASRc controller often has to limit the CSS values due to high hydraulic pressure. This somehow capped the potential of the proposed algorithm. Similar work was reported by the same authors on the dynamic optimization of crushing circuits in a series of publications culminating in [18], in which an evolutionary operation (EVOP) algorithm was proposed for the eccentric speed control of a cone crusher in a crushing circuit, aiming to optimize the performance of the circuit in terms of product throughput.

In this paper, a centralized control strategy is proposed to increase the product throughput of a crushing circuit. For this scenario, an FSM controls the efficiency of the crushing circuit, manipulating the CSS of the crusher and the speed of the feeder that extracts material from a buffer silo located after the crusher and before the screens. A preliminary study evaluated performance results for different operating points and the admissible ranges of the CSS. This analysis indicates an inverse relationship between the product throughput and the quality of the crushed material. Thus, the FSM algorithm tries to keep the operating CSS at its minimum value (35 mm) for as long as possible, taking into account safety aspects of the operation with respect to the levels of the storage silos and the power consumption of the crusher, regardless of the feed ore composition. If the raw material has ore with a higher hardness index, the CSS is increased to ensure that constraints on power consumption and pressure in the crusher are respected (to reduce the number of plant stops) at the expense of increasing the recirculating load and decreasing the product throughput.

To investigate the performance of the proposed control strategy, a crushing circuit model is simulated using commercially available dynamic simulation software (IDEAS®). The simulated crushing circuit was validated using operational data collected from the Serra Leste iron plant, operated by Vale S.A. in Brazil. The case study presented here showcases a typical crushing circuit from mineral processing plants, and by considering buffer silos levels before and after the crusher, it is possible to create additional degrees of freedom for the control problem. In addition, the comprehensive simulation bed allows for the investigation of the performance of the crushing circuit under disturbances in feed hardness, size distribution, and flowrate. The proposed control strategy is compared to a fixed CSS setting, and the simulated results show that, in some cases, it can increase the throughput of product from 438.65 t/h to 675.31 t/h, corresponding to an improvement of 53.95%. This increase in product throughput is a consequence of the reduction in variability and the number of plant stops.

The selection of the proposed control strategy based on FSM is primarily attributed to its simplicity, in terms of both its development and maintenance. Mining plants are often situated in remote areas, which poses a challenge in terms of hiring and keeping trained personnel [20,21]. Consequently, the design and maintenance of sophisticated control strategies, such as hybrid model predictive control, adaptive control, and neuro-fuzzy, are often difficult to implement and maintain. Therefore, many mining plants worldwide continue to require uncomplicated control strategies capable of enhancing productivity in such settings.

The main contributions of this study are as follows: First, it proposes a centralized controller for a sector of a crushing circuit (feeding–screening–crushing) to enhance production by maximizing the operational time of the process without reaching interlocks. Second, the paper introduces a novel approach by employing silos levels, crusher CSS, and screen feed flow rate as manipulated variables for the controller. Third, the proposed controller is evaluated using a realistic crushing circuit model and long-term data obtained from an iron ore plant, providing evidence of its effectiveness in practical applications. Lastly, the paper provides a set of recommended steps for tuning the parameters of the FSM used in the proposed controller, thereby facilitating its implementation in other similar contexts. Overall, this paper presents a comprehensive approach to improving crushing circuit operations and provides valuable insights into the design, implementation, and evaluation of centralized control strategies in the mining industry.

This paper is organized as follows: In Section 2, the crushing circuit is described. In Section 3, the control problem of the crushing circuit under study is discussed. The application of the proposed control strategy to the crushing circuit is presented in Section 4. The results attained using the proposed control strategy are presented in Section 5. Finally, in Section 6, the conclusions are discussed.

2. Crushing Circuit Flowsheet Description

Figure 1 shows the crushing circuit from the Serra Leste iron mine addressed in this work. The mine is operated by Vale S.A. in Brazil and produces approximately 6 million tonnes of iron ore per year. The cone crusher (CC) is fed to the circuit on the same conveyor belt (CB1) that carries the crushed material from the cone crusher (CC). The maximum capacity of CB1 is 2094 t/h. The raw material comes from a primary crushing/screening circuit at around $P_{80} = 125$ mm, and the CSS of CC is a manipulated variable of the circuit and can take values of 35, 38, or 41 mm.

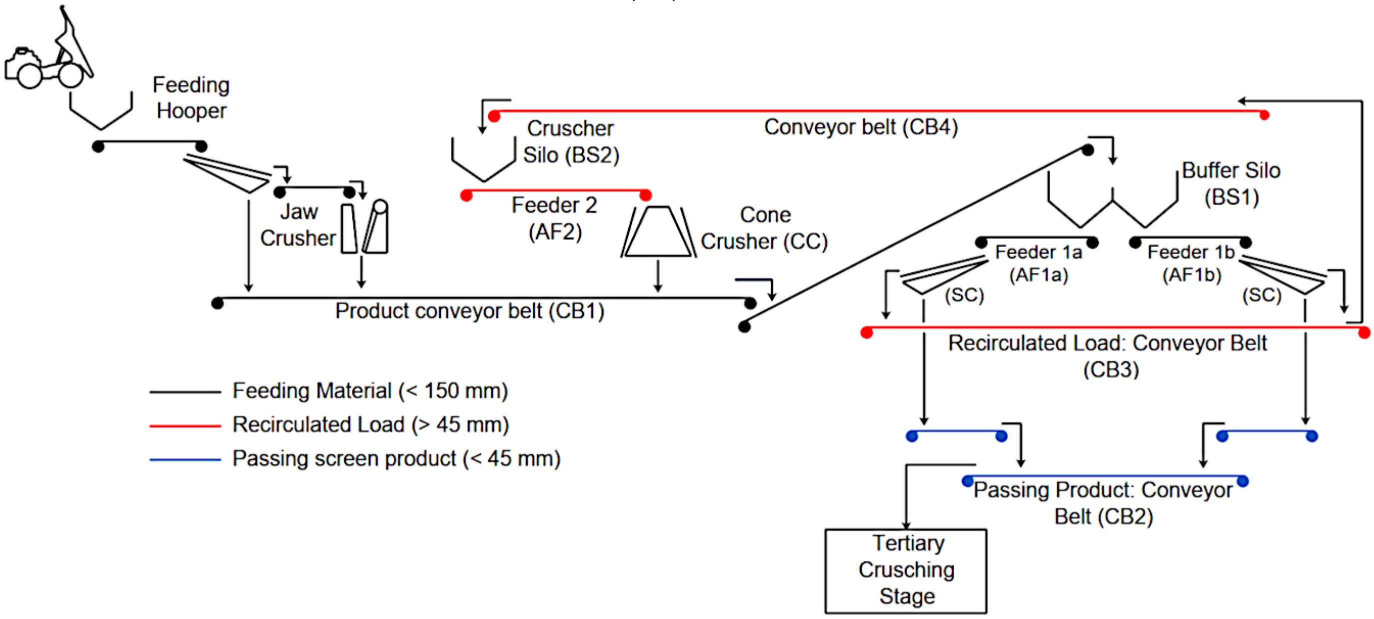


Figure 1. Flow chart of the crushing circuit at Serra Leste.

The mixed material stream is carried to buffer silos (BS1). The material in BS1 is fed to the screening circuit (SC) by two apron feeders (AF1a, AF1b). AF1 has a total capacity of 1959 t/h, and the speed is adjusted by a PI controller (PI_{SC}) that tries to keep the level of BS1 at 80%. The undersize of SC with a size cut of 45 mm is the final product of this crushing circuit and is carried to downstream processing stages by a conveyor belt (CB2) with a maximum capacity of 718 t/h. The oversize of SC is carried to another buffer silo (BS2) by two conveyor belts: CB3 and CB4, both with a maximum capacity of 2133 t/h. Then, the material in BS2 is fed to CC by an apron feeder (AF2). The speed of AF2 is also adjusted by a PI controller (PI_{CC}) that tries to keep the level of material inside the CC at 70%. The purpose of manipulating AF2 is just to keep the crusher chamber level at the appropriate value. In this way, the crusher works efficiently.

The raw material coming from the upstream process can vary in quantity, hardness, particle size distribution and moisture level. These factors are treated as disturbances in the control problem, as explained in Section 3. The goal of the crushing circuit is to deliver as much product as possible at $P_{80} \leq 45$ mm.

The interlock rules are summarized in Table 1. These interlocking conditions are defined by plant specialists and are implemented to guarantee operational safety and equipment integrity. The wide range between interlock and recovery conditions is defined to ensure a consistent return to regular operation, i.e., avoid further triggering of interlocks in sequence. Without this range, a new interlock may occur shortly after the recovery of the regular condition, resulting in the unstable behavior of the plant and greater wear of the equipment.

Table 1. Interlocks of the Serra Leste crushing circuit.

	Interlock Condition	Action	Goal	Recovery Condition
1	Level of BS2 above 95%	Shut down AF1, CB3, CB4	Prevent overflow in BS2	Level of BS2 below 70%
2	Level of BS2 below 10%	Shut down AF2	Avoid loading damage in BS2	Level of BS2 above 20%
3	Level of BS1 above 90%	Shut down CB4, CB3, RAW	Prevent overflow in BS1	Level of BS1 below 60%
4	Level of BS1 below 10%	Shut down AF1	Avoid loading damage in BS1	Level of BS1 above 20%
5	Load of CB3 above 2133 t/h	Shut down AF1	Avoid overloading CB3	Load of CB3 below 2133 t/h
6	Load of CB2 above 718 t/h	Shut down AF1	Avoid overloading CB2	Load of CB2 below 718 t/h

3. Problem Description

The purpose of the crushing circuit control system presented here is to increase the product throughput while ensuring that all equipment operates within safety levels, according to the interlocking rules listed in Table 1. Furthermore, the product must meet quality specifications. However, in a run-of-mine mineral processing plant, the composition of the feed ore changes regularly and the characteristics of the feed ore, such as ore hardness and particle size distribution, vary. In addition, for complex crushing circuits, stability and good performance may be difficult to achieve, as the circuit may have multiple parallel flows, re-circulation mass, large time delays, partial integration of different stages and coupling between control variables [22]. Thus, the crushing circuit is challenging to operate manually due to complex process behavior and various unknown disturbances. The control objective can be summarized as being to increase production in a holistic way by increasing the product throughput when the plant is operating and by reducing the time in which the plant is not operating because of an interlock event.

In the control strategy currently implemented at Serra Leste iron mine, hereafter addressed as MANUAL, the control loops for the feed section and the screening section are implemented in a non-integrated manner, following the safety recommendation from the interlock rules presented in Table 1. Such interlocks have a double-edged effect on production: on one hand, they ensure safe operation (by shutting down the plant before any accident), but on the other hand, they cause undesired plant stops that might halt production for a long time. Note that the MANUAL control strategy does not consider interactions between different sections of the circuit. In the absence of an integrated control system, the plant operator is responsible for choosing the proper operating conditions for the crushing circuit equipment. Thus, manual operation of the crushing circuit to enforce operation constraints and increase product throughput (and consequently the economic profit) requires extensive knowledge of the process behavior and frequent monitoring to compensate for disturbances.

The problem of the crushing circuit under study is that the MANUAL control system, in addition to disturbances in the properties of the raw material, can lead the operation to dangerous and unwanted conditions, such as when the energy consumption in the cone crusher is too high or when one of the buffer silos is about to overflow with material. Such dangerous and unwanted operating conditions in the MANUAL control strategy often lead to interlock events (when any of the operating constraints in Table 1 are violated). Equipment interlock leads in turn to plant shutdown, which reduces productivity and, therefore, the efficiency of the crushing circuit. To overcome the problems described, there are additional degrees of freedom available that allow for integrated operation of the control system. In this sense, the proposed control strategy uses the buffer silos before and after the cone crusher together with the apron feeder for the screening section. In addition, the proposed control strategy seeks to increase product throughput by keeping the CSS at its lowest setting (35 mm) for as long as possible.

4. Development of the Centralized Control System

In this section, control objectives are defined to increase the product throughput of the crushing circuit. Then, the proposed centralized control system algorithm is presented.

As described in Section 3, the MANUAL control strategy of the crushing system at the Serra Leste plant is non-integrated, which means that the controllers do not consider the interactions between the different parts of the process. Most of the time, the fixed value for the CSS of the cone crushers is defined by the operator depending on the characteristics of the ore that is fed into the circuit. However, both the quality and size distribution of the feed material change over time.

4.1. Definition of Control Objectives

The main objective of the crushing circuit control system proposed in this study is to increase the product throughput, which means producing the largest possible amount of product with granulometry below 45 mm. The highest productivity of the Serra Leste crushing circuit is obtained with the cone crushers operating with a CSS equal to 35 mm as long as possible. The reason for this can be understood from the observation of the passing size distribution (PSD) for the crusher with different CSS values, shown in Figure 2. Note that for a CSS equal to 35 mm, the cumulative pass of material at the crusher output is higher when compared to a CSS equal to 38 and 41 mm. Figure 3 illustrates the iron ore sampled at the crusher output with different CSS values. As a consequence of setting the CSS to 35 mm, the recirculating load of the CB3 conveyor belt is smaller and, consequently, the amount of material that actually becomes product ($P_{80} \leq 45$ mm) in CB2 is greater. Thus, the idea of the proposed control system is to set the CSS equal to 35 mm for as long as possible regardless of the type of material that feeds the circuit and the operating conditions of the circuit. Therefore, the control strategy must make a series of changes to maintain these desired operating conditions without triggering the interlocks described in Table 1.

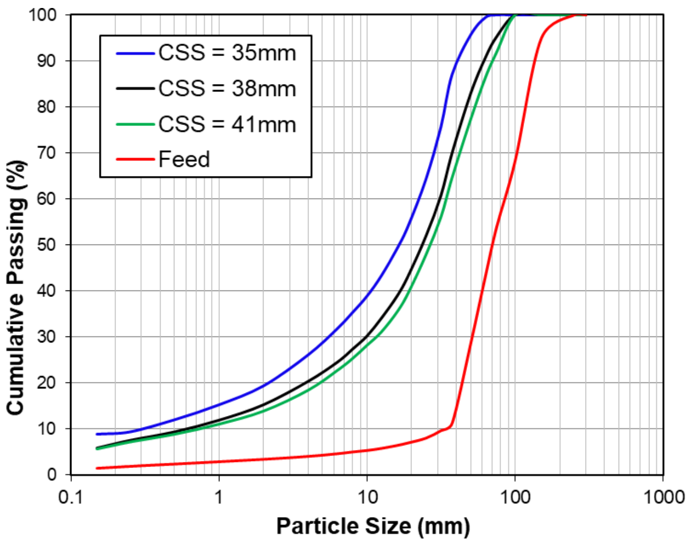


Figure 2. Passing size distribution curves of crushed material for different CSS.

(**a**) Feed material. (**b**) CSS in 35 mm. (**c**) CSS in 38 mm. (**d**) CSS in 41 mm.

Figure 3. Sampling of iron ore with different passing size distribution.

4.2. Proposed Control Algorithms

From the described control objectives, the FSM algorithm was introduced. A simple variant of the FSM called the Mealy machine is used, in which actions occur only at the entry of a state. The output of a state depends on the different conditions established for a given operating condition. Two FSM algorithms were developed: the first FSM, shown in Figure 4, is used for operation in the event of interlocking in the crushing circuit; the second FSM, shown in Figure 5, is designed for regular operating conditions. Tables 2 and 3 summarize the set of states, inputs, and outputs of the proposed control strategy. The following sections describe each FSM in detail.

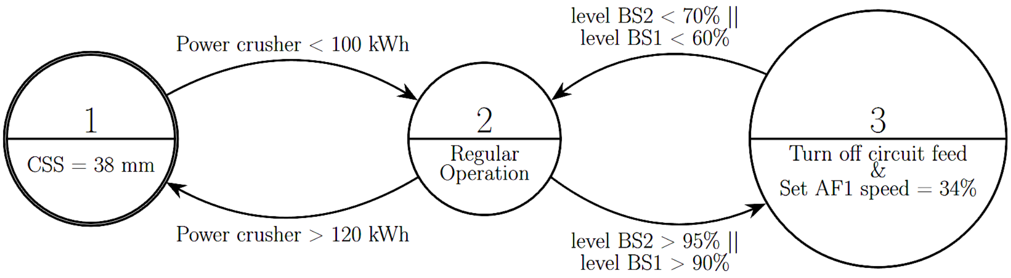


Figure 4. The FSM used during interlock conditions.

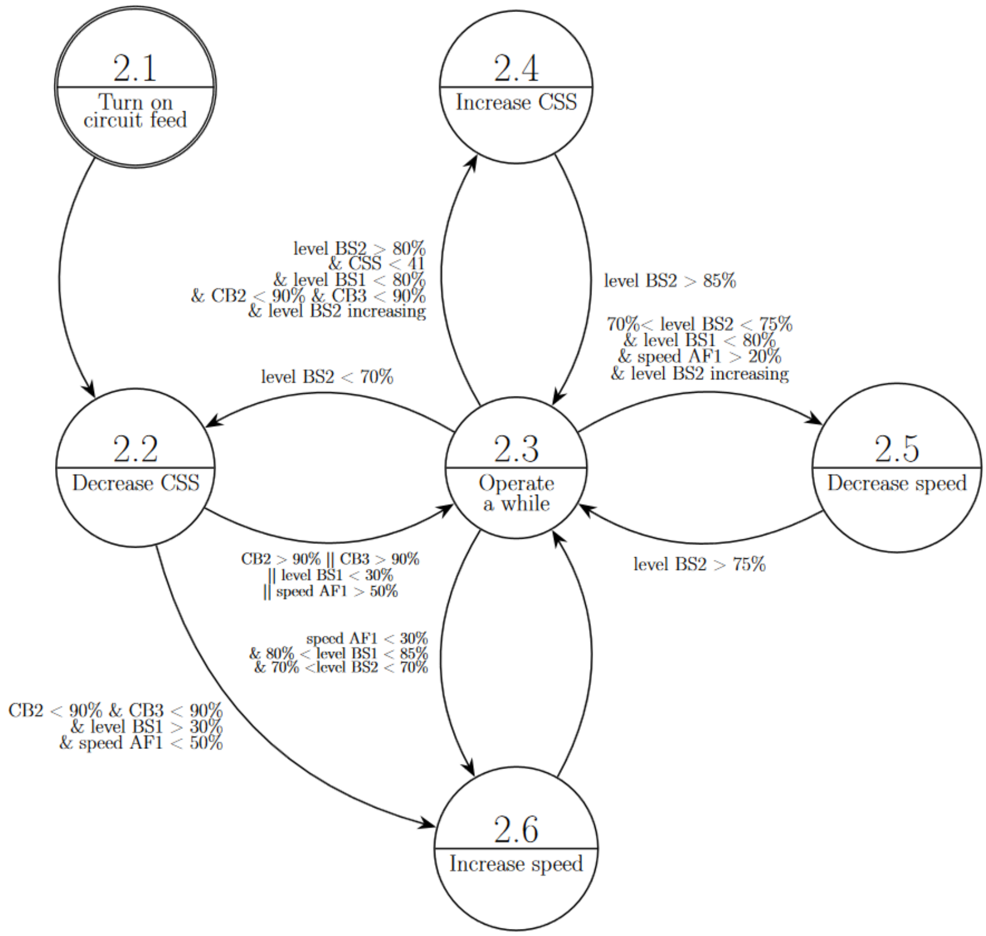


Figure 5. The FSM used during regular operating conditions.

Table 2. Set of states of the proposed control strategy.

	States	
	Number	**Condition**
Unsafe conditions	1	CSS = 38 mm
	2	Regular operation
	3	Turn off circuit feed and set AF1 speed
Regular operation	2.1	Turn on circuit feed
	2.2	Decrease CSS
	2.3	Operate a while
	2.4	Increase CSS
	2.5	Decrease speed
	2.6	Increase speed

Table 3. Sets of inputs and outputs of the proposed control strategy.

	Inputs	Outputs
Unsafe conditions	Power crusher Level BS1 Level BS2	CSS AF1 speed Circuit feed
Regular operation	Level BS1 Level BS1 Capacity of conveyor belt CB1 Capacity of conveyor belt CB2 Capacity of conveyor belt CB3 AF1 speed	CSS AF1 speed Circuit feed

4.2.1. The FSM Used in Case of Unsafe Conditions

The FSM used in case of the unsafe operation of the crushing circuit equipment is illustrated in Figure 4. This FSM works similarly to a watchdog, which implies that in the event of undesired or unsafe operating conditions, actions are taken to minimize damage to the crushing circuit equipment. Thus, the condition to reach state 1 occurs if the crusher power reaches a value greater than 120 kWh. Then, the CSS is set to 38 mm, an intermediate value between 35 and 41 mm. State 1 is maintained as long as the crusher power has not decreased to the specified value. On the other hand, state 3 is reached when silos BS1 and BS2 exceed their acceptable levels. In this case, the speed of AF1 is set to 34% and new material feeding is disabled. In this way, the emptying of the silos is awaited to return the raw material feed. Note that interruption of raw material coming from the mine is undesirable, and this state should be avoided. The other variables of the crushing circuit are not changed.

Note that the proposed control strategy allows the return to regular operation, defined in state 2, only after the defined time and the crusher power is less than 100 kWh and/or when the BS1 and BS2 levels decrease to safe values.

4.2.2. The FSM Used in the Case of Regular Conditions

The FSM for regular crushing circuit operation is designed to keep the CSS at 35 mm as long as possible. However, keeping the CSS fixed at 35 mm for long periods of time could lead to interlocking due to increased levels of silos BS1 and/or BS2 or increased crusher power. As described in Section 2, the PI_{CC} controller manipulates the speed of AF2 to keep the level inside CC at 70%. This controller does not consider the BS2 level or any other variable. Once the steady state of operation is reached, an increase in the BS2 level occurs due to the increase in the recirculated load. To overcome this problem, in the proposed control strategy, the speed of the feeder AF1 is manipulated and the silo BS1 works as a buffer. In addition, if the BS2 level continues to increase, the CSS must be increased. Thus, it is possible to reduce the BS2 level without stopping production. The FSM shown in Figure 5 implements these described operating conditions. Note that during regular operation, if the BS2 level is less than 70%, the "decrease CSS" state is reached (state 2.2). This state always decrements the CSS by 3 mm. Thus, allowable CSS values for the crusher are 35, 38, and 41 mm. Then, depending on the level of BS1 and capacity of conveyor belts CB2 and CB3, it is possible to increase the speed of feeder AF1 by 10% (State 2.6). The purpose of this action is to increase the amount of product sent to the next stage of the crushing circuit. Always after an action, the control system reaches state 2.3 operating for a while to wait for the effects of the actions taken.

If the BS2 level increases above 70%, the speed of feeder AF1 is reduced by 10% (state 2.5). Thus, the amount of recirculated load is reduced and the circuit operates longer with the CSS at 35 mm. The purpose of this action is to avoid interlocking due to the high level of the BS2 silo.

The conditions to increase CSS (state 2.4) occur when the BS2 level is increasing and higher than 80%, CB2 and CB3 conveyor belts have capacity lower than 90%, and the BS1 level is lower than 80%. The purpose of this action is to keep the circuit operating, even outside the desired operating condition, i.e., CSS equal to 35 mm. Thus, the control waits for the crushing circuit to operate under conditions that allow reducing the CSS again.

4.2.3. The FSM Tuning Procedure

The procedure for tuning the FSM parameters aims to increase the productivity of the crushing circuit considering the trade-off between performance and robustness. These values are obtained based on the interlocking conditions described in Table 1 and observing the operating conditions of the plant by a multidisciplinary group of specialists.

Initially, a group was established comprising representatives from various departments, namely operation, control room, automation, maintenance, and process engineering, with the objective of tuning the parameters of the proposed FSM. Given the method's inherent simplicity and the considerable expertise possessed by the participants, only three meetings sufficed to successfully accomplish this endeavor, resulting in a unanimous consensus on the selected parameter values. In addition to the primary outcome of a finely tuned controller, ancillary benefits emerged from this undertaking, including enhanced involvement of the team in the development process and the dissemination of a comprehensive understanding of the proposal to all key stakeholders within the mineral processing plant.

The tuning procedure encompassed three primary stages. First, the range of feasible values for the manipulated variables was established. Subsequently, we addressed the stringent safety criteria that must be adhered to. Lastly, we accounted for the conveyors' and silos' capacity limits in transitioning between states, aiming to enhance performance by increasing speed or reducing the CSS, or bolstering robustness by decreasing speed or increasing CSS. Consequently, the principal outcomes are systematically structured as follows:

1. The allowable values for the CSS were predetermined to be 35, 38, and 41 mm, whereas the allowable range for the AF1 speed spanned from 20 to 100% in increments of 10%. These values were chosen considering both equipment limitations and the significance of minor variations in the system.
2. The hard safety requirement was defined as the electrical power consumed by the crusher. This variable cannot surpass 120 kWh to avoid damage.
3. The group defined the limits for silo levels and conveyor capacities for state transitions so that an interlock would occur in roughly the next hour. In this way, we formulated the following question to guide us: *What is the necessary silo/conveyor belt capacity to accommodate a flow rate equal to the midpoint of the range plus 20%, while simultaneously maintaining the output flow rate at the midpoint of the range?* With this in mind, it follows that the answer lies in the required reminiscent capacity in the silo or conveyor belt to keep the circuit running without interlocking. These values are translated to simple inequalities in the FSM diagrams. Note that the system is dynamic, and those assumed stream rates of difficulty remain for an entire hour. Nevertheless, the group of specialists agree that the adopted assumption exhibits sufficient conservatism for this specific circuit and holds practical utility in operational contexts.

Throughout the specialist group meetings, draft FSM diagrams were consistently presented for examination, while historical data were also made available for consultation and analysis. The tuning outcomes were subsequently incorporated above the arrows representing the transitions between states, subsequent to each technical discussion. Ultimately, complete diagrams were rendered and are displayed in Figures 4 and 5. It is essential to emphasize that the objective of this approach does not lie in finding an optimal solution. Instead, the focal requirements encompass simplicity and the involvement of numerous employees, thereby maximizing the probability of long-term success for the controller.

5. Results and Discussion

In this section, the results obtained with the proposed control strategy based on the FSM are presented and compared with fixed CSS operation. The crushing circuit model of Serra Leste is simulated using the dynamic simulation software IDEAS®.

Four scenarios were simulated according to constant feed throughput set at 600 t/h, different $d80$ of iron ore and fixed or dynamic bond ore work index (BWI). The constant value of 600 t/h represents the usual operating value of the feed throughput of the crushing circuit under study. These operating conditions are defined as the input of the crushing circuit simulator, i.e., the material that comes from the mine and feeds the feeding hopper; see Figure 1.

The BWI index is used to indicate the hardness of the iron ore fed into the crushing circuit. Different methods are proposed in the literature with the aim of calculating the BWI in several scenarios [23]. According to [24], empirical methods that allow a direct calculation of BWI using a simple procedure are often more suitable for application to plants. For scenarios with a fixed BWI, its value is equal to five, which consists of the average BWI of the ore fed into the circuit obtained from laboratory tests. On the other hand, the dynamic value of the BWI is defined from the lower and upper limits of a set of ore samples from the crushing circuit. In this case, from historical data, a sinusoidal function is defined with a frequency of 0.0001 rad/s. Thus, the dynamic value of the BWI presents a slow and gradual variation in hardness similar to the characteristics of the iron ore fed into the crushing circuit of the Serra Leste processing plant. Hence, the following sinusoidal function is used:

$$\mathrm{BWI}(t) = 7.5 + 2.5 sin(0.0001t). \tag{1}$$

The following scenarios are considered:

- Scenario 1: $d80 = 121.96$ mm and fixed BWI;
- Scenario 2: $d80 = 87.76$ mm and fixed BWI;
- Scenario 3: $d80 = 121.96$ mm and dynamic BWI;
- Scenario 4: $d80 = 87.76$ mm and dynamic BWI.

5.1. Simulation Environment

The crushing circuit simulator is configured according to the process parameters and capabilities of each of the pieces of equipment that make up the crushing circuit of Serra Leste. The conveyor belts, apron feeders, silos, screens and cone crusher (Metso HP400, Espoo, Finland) were modeled using the default blocks from IDEAS®, and parameters such as belt length and screening efficiency were set to closely represent the actual crushing circuit.

The centralized control system based on the FSM was implemented in Simulink®. The developed FSM algorithm is integrated with the crushing circuit simulator via an OPC (Open Platform Communications) server. In this framework, the OPC works as a bridge between IDEAS® and Simulink®. The OPC client uses the OPC server to obtain data from or send commands to the simulator in a sampling time of 1 second. Figure 6 illustrates the framework of the control system with crushing circuit simulator.

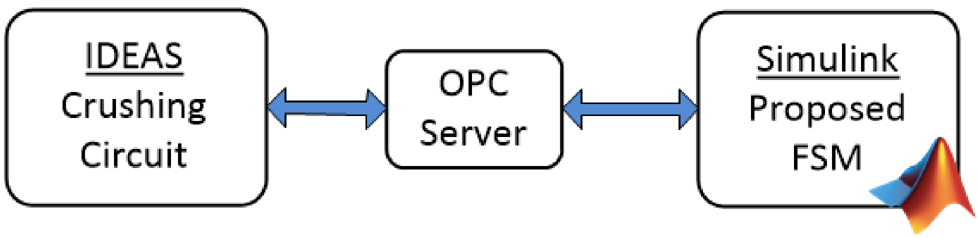


Figure 6. Schematic diagram of the integration of the Serra Leste circuit simulator and proposed control strategy.

5.2. Simulation Results

For all scenarios considered, the simulation time is equal to four hours. This value is defined according to the dynamics of the crushing circuit to evaluate the steady-state response in different scenarios. The results obtained with the proposed approach are compared with the CSS fixed operation, which is the usual practice for operating the cone crusher in Serra Leste.

The simulation always starts with the silo level at 50% and all conveyor belts, feeders and crushers empty. This initial crushing circuit condition is chosen to evaluate the transient response of the proposed control system during scenarios such as plant startup or return from an interlock condition. Also, for both decreasing and increasing, the CSS variation is 3 mm. The speed of AF1, whether decreasing or increasing, is always changed by 10% of the current value. The parameters of the FSM algorithms are set as described in Section 4.2.3 to achieve the maximum product throughput. Furthermore, the same set of parameters is considered independent of the evaluated scenario.

Table 4 summarizes the results obtained with the proposed control strategy for all scenarios. The lower specific consumption obtained with the proposed strategy indicates the greater operational efficiency of the crushing circuit. The performance of the crushing circuit is evaluated based on the average value of the product throughput, which translates into the average value of the passing product rate on the conveyor belt (CB2) over the simulation time. Figure 7 shows the average value of the product throughput obtained in all scenarios. Note that with the proposed control strategy, in all scenarios, an increase in product throughput is obtained when compared to non-integrated operation and fixed CSS.

Among the simulated scenarios, the third ($d80 = 121.96$ mm and dynamic BWI) is chosen for the discussion, in detail, of the results obtained with the proposed control strategy from the dynamics of the main variables of the crushing circuit. Figure 8 shows the levels of silos BS1 and BS2 in scenario 3. Note that for a fixed CSS, there is always a BS2 level interlock triggering, and the time this interlock occurs depends on the CSS value. For a CSS equal to 35 mm, the BS2 interlock occurs later than the operation with CSS at 41 mm because in the case of 35 mm, the amount of recirculated material is smaller, that is, more product passes through the screening circuit.

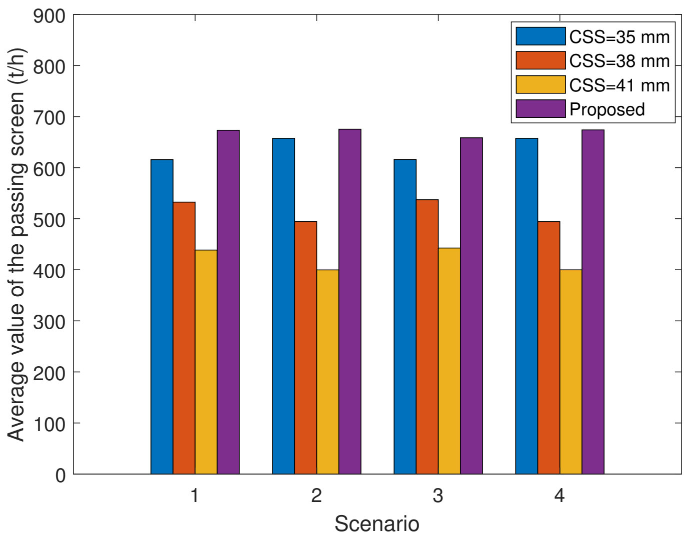
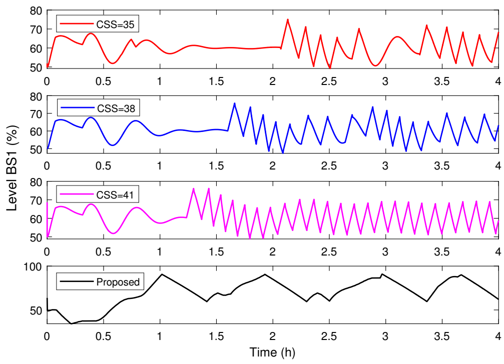


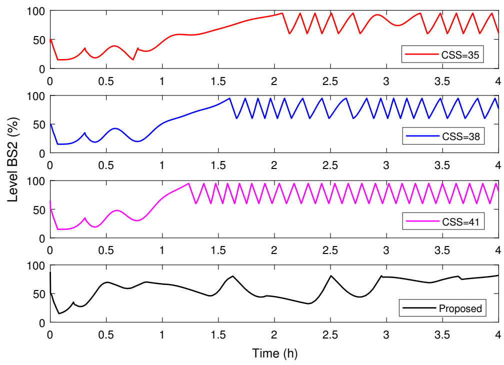
Figure 7. Production throughput performance in different scenarios.

Table 4. Average value of passing material in secondary crushing screens for fixed CSS values and proposed control strategy.

Scenario	CSS	Average Valute of Passing Product Conveyor Belt (t/h)	Specific Consumption of CC (kWh/t)
1	35	615.92	0.1416
	38	532.52	0.1479
	41	438.65	0.1523
	Proposed	673.25	0.1174
2	35	657.42	0.0922
	38	494.62	0.1009
	41	399.75	0.1017
	Proposed	675.31	0.0912
3	35	616.09	0.1416
	38	537.17	0.1481
	41	442.6	0.1512
	Proposed	658.48	0.1179
4	35	657.44	0.0921
	38	494.35	0.1012
	41	399.85	0.1017
	Proposed	673.91	0.0916



(**a**) Level of buffer silo (BS1).



(**b**) Level of buffer silo (BS2).

Figure 8. Levels of silos for scenario 3.

For operation with a fixed CSS, the feeder speed is set only from silo-level BS1. Therefore, the apron feeder speed (AF1) continues to increase in an attempt to bring the level to its setpoint (see Figure 9). However, due to the interlocking of the buffer silo BS2 for a level above 90%, AF1, CB3 and CB4 are turned off (see Table 1). In this way, as shown in Figure 8a, there is high variation between 50 and 75% in the BS1 level due to the interlocks caused by the BS2 level. In contrast, for the proposed control strategy, there is no interlocking of the BS2 level; consequently, the amount of ore that becomes product is greater than that in the operation with a fixed CSS. For the proposed control, also note that the variation of the BS1 level actually acts as a buffer, that is, this level varies smoothly throughout the operation of the crushing circuit. This result is obtained by changing the feeder speed AF1, as shown in Figure 9.

Also for scenario 3, Figure 10 shows the recirculated load in CB3 and passing product in CB2. According to Table 1, in the event of level interlock in silo BS2, conveyor belts CB2 and CB3 must be turned off. Since several interlocks occur in the operation with a fixed CSS, CB2 and CB3 are turned off. In this case, less material becomes product, which directly impacts the productivity of the crushing circuit. On the other hand, for the proposed control strategy, there is continuity in the operation of the CB2 and CB3 conveyor belts, which results in a higher product throughput.

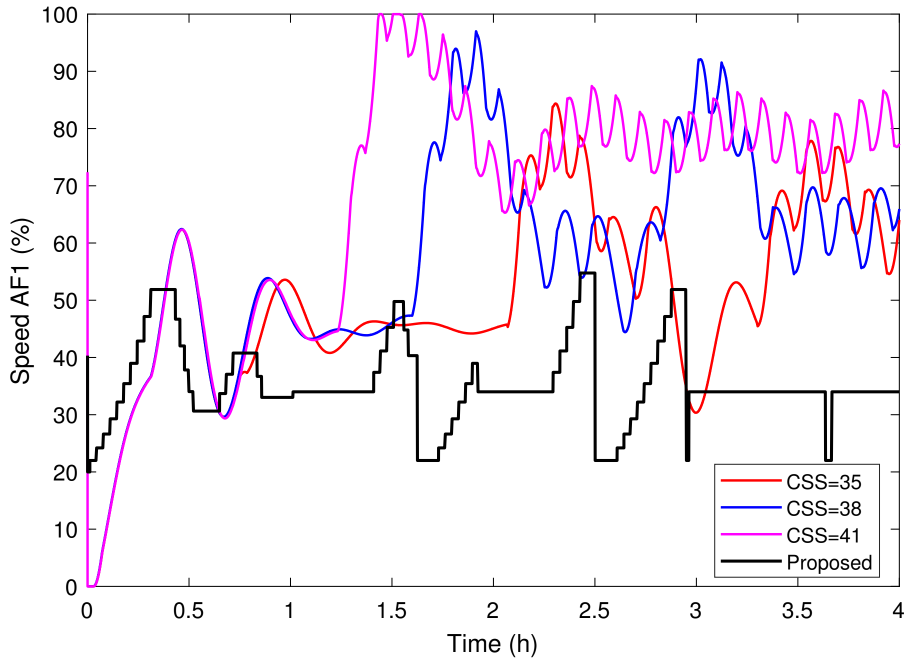
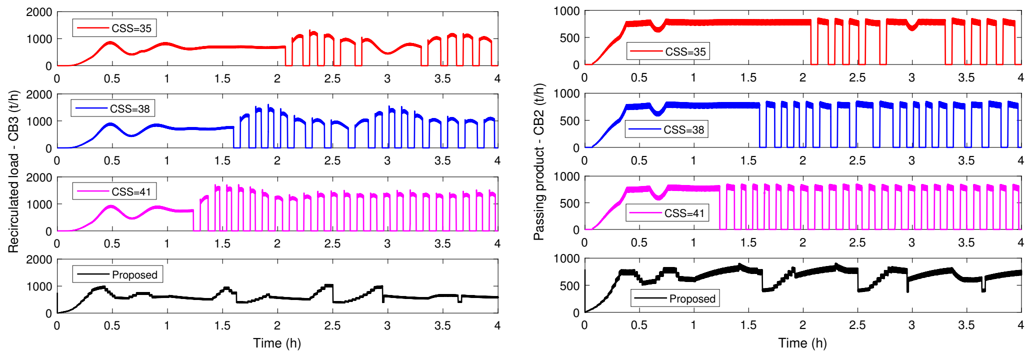


Figure 9. Speed of feeder AF1 in Scenario 3.



(**a**) Recirculated load (conveyor belt 3). (**b**) Passing product (conveyor belt 2).

Figure 10. Flow rate of conveyor belts 2 and 3 for scenario 3.

Another action necessary to avoid interlocks during crushing circuit operation is to change the CSS. Figure 11 shows the CSS variation for scenario 3. As defined in the control objectives in Section 4.1, most of the time, the CSS is kept at 35 mm and the CSS increases only when the BS2 level rises above 80%. This action aims to guarantee the operation of the crushing circuit without interruptions. Considering the BS1 and BS2 levels, feeder speed, and CSS change in an integrated manner, it is possible to operate for a longer time with the CSS at 35 mm, avoiding the activation of the interlocks and guaranteeing an increase in the productivity of the crushing circuit.

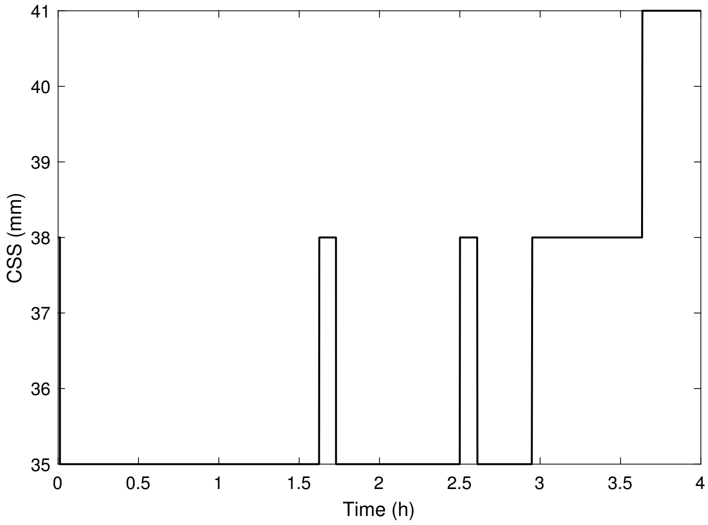


Figure 11. CSS of the proposed control strategy in Scenario 3.

For scenario 3, Figure 12 shows the average values of material at the crusher output and product throughput for fixed CSS and the proposed control strategy. According to this figure, the integrated action of the control system based on the FSM algorithm has achieved the objective of maximizing the product throughput, which means less material recirculating and an increase in the product rate passing through the CB2 conveyor belt. In this case, compared to the fixed CSS at 35 mm, there is an increase of 6.88% in the average value of the product passing through the conveyor belt. When compared to CSS fixed at 41 mm, the average productivity increase is 48.77%. Therefore, the simulation results demonstrate that the proposed control strategy can establish greater productivity through operation with the CSS at 35 mm, without the need to interrupt production due to the interlocks.

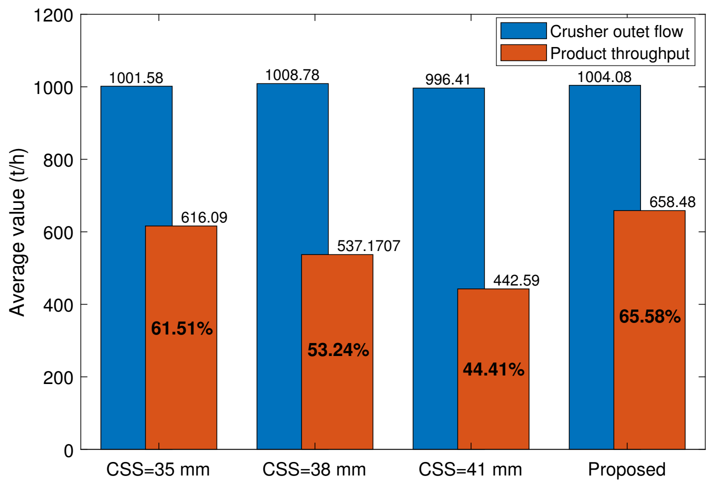


Figure 12. Performance with throughput equal to 600 t/h, *d*80 of 121.96 mm and dynamic BWI (Scenario 3).

6. Conclusions

In this paper, a centralized control strategy based on the FSM algorithm was proposed to increase the product throughput of the crushing circuit of the Serra Leste iron plant, operated by Vale S.A., in Brazil. Since the crushing circuit under study presents non-integrated control, depending on the operating conditions, undesired operation may occur. From a practical perspective, some conditions could lead to plant shutdown, which reduces productivity and, therefore, the efficiency of the crushing circuit. Thus, the proposed solution seeks to increase the circuit operation under both regular conditions and interlocking. Changes in the CSS of the cone crusher and speed of the apron feeder are considered to achieve this goal. Different scenarios were considered, varying the $d80$ and BWI of the feed material. The proposed control strategy was compared with the operation of fixed CSS values, which is the common practice in the plant. Regardless of the evaluated scenario, an increase in average productivity is observed with the proposed controller. The results illustrate the added value of using a centralized control strategy when compared to operating on a fixed CSS, even when the fixed value is the one that intuitively maximizes output, i.e., the lowest CSS equal to 35 mm. In this case, with $d80 = 121.96$ mm and dynamic BWI, an average increase of 6.88% in productivity is observed. Compared to that under operation with the CSS fixed at 38 mm, the productivity has an average increase of 22.58%. On the other hand, when comparing the operation on the largest CSS, the average increase is 48.77%. In addition to the benefit of increased productivity, the proposed control strategy contributes further to more stable operation, reflected by the elimination of interlocks during the simulated time and overall smoother recirculating load and product throughput flowrate oscillations. This, in turn, increases the reliability and predictability of the crushing circuit and decreases maintenance costs. Future work will include the definition of the FSM algorithm parameters using a reinforcement learning approach, experimental validation of the proposed control strategy, and the inclusion of variables from the tertiary and quaternary crushing stage to increase the production of a specific product, for example, sinter feed. Advanced control strategies, such as [25,26], will also be evaluated and compared with the proposed control algorithm. Furthermore, a theoretical analysis of the stability and robustness properties of the proposed controller can contribute to advancing its industrial viability and acceptance. Finally, environmental analysis will also be carried out with a focus on reducing emissions and improving resource efficiency.

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Abbreviations

AFn	Apron feeders
BSn	Buffer silo
CBn	Conveyor belt
CSS	Closed-side-setting
BWI	Bond work index
CC	Cone crusher
EVOP	Evolutionary operation
FSM	Finite state machine
PSD	Passing size distribution
PID	Proportional–integral–derivative
OPC	Open platform communications
SC	Screening circuit

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