Flow Optimization for Iron Ore Reclaiming Process

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Abstract: The purpose of the this paper is to demonstrate the optimization of the flow for the iron ore reclaiming process by reclaimers over rails using implementation of PID control algorithms, identification techniques, Predictive Control and a new effort-based learning method herein called reinforcement by difference learning method and proportional reinforcement learning method. The outcome was an increase of productivity, with reduction of the flow variability and on the amount of overflow occurrences.

1 INTRODUCTION

The need to control physical processes and systems exist since remote times. The manual control, first way for controlling used by man and still found in many processes nowadays, shows the need of a human operator that must know the system and have reasonable experience and skills. With the sophistication increase of human activities came along the interest and necessity to automate or semi-automate some processes, this was possible due to the scientific and technological development that among some several other knowledge brought us the classical control theories. However, with the advance of technology, systems and processes became more complex making ineffective, or even impossible, the usage of conventional controllers obtained from classical theories. This initiated a search for new methods and strategies for control such as: multivariable control, adaptive control, predictive control and intelligent systems control.

Figure 1: Stacker-Reclaimer at TMPM.

This paper demonstrates the application of techniques for identification and process control n stacker-reclaimers/reclaimers over rails located at Terminal Maritimo Ponta da Madeira (TMPM).

The Terminal Maritimo Ponta da Madeira, located in Brazil at the city of São Luis-MA, belongs to VALE and is composed, currently, by 4 car dumpers with nominal capacity of 8,000 tons per hour, ten iron ore stock yards, conveyor belts and 10 yard machines divided in: 3 stackers, 3 reclaimers, 4 stacker/reclaimer and 4 ship loaders, all used to ship iron ore.

2 OPERATIONAL MODES FOR RECLAIMING

Reclaimers installed at TMPM can use 3 (three) modes to control the reclaiming process:

- Local
- Manual
- Semi-Automatic

The work for optimization was done to improve the performance only for the semi-automatic operation mode.

2.1 Local Mode

This mode purpose is for maintenance or testing and will be executed through action from the maintenance technicians on the command buttons located nearby the equipments and respecting all the security interlocks, not being possible in this mode

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any productive process. All equipments are commanded via the CLP.

2.2 Manual Mode

In order to characterize the manual mode, only is needed to have selected on the HMI or in the SOS (system operating station), the operation from CABIN or CONTROL ROOM and, additionally, have been selected the MANUAL mode. The signaling will be through MANUAL OPERATING ROOM or MANUAL CABIN written on the operating screen.

The reclaiming will be under the command of the operator through the usage of the levers at the console. In this mode also the security and process interlocks are respected, disallowing start them out of sequence.

The translation movement will not revert automatically and, the material reclaiming can be done in any area of the stock yar d as long as the operator detects it available.

The equipments will be commanded individually via CLP, as long as the yard's conveyor belt is on (Start Conveyor of Spear and Start Bucket Wheel)

2.3 Semi-Automatic Mode

In this operating mode, the operator establish the parameters of the process such as initial and final landmark, set point for the reclaiming flow rate and the time or distance for advancing and the angles for the reversal of spear rotation.

Initially, through the rotation lever, the movement is commanded and reversal points are marked. The marked points are memorized and after this marking, every time the rotation angle reaches these points, there is a reversion of this movement. Through the operating console it is possible to reset the information of reversal points previously defined, allowing a new preset for adjustment of the reversal point.

In this mode, the backing movement and spear descent for changing the reclaiming stand are done manually, being necessary reinitiate de reclaiming process, marking new reversal points for the spear rotation.

The rotation speed is controlled through a PID control loop and the time for the translation step is determined by the operator as well as may be adjusted automatically by a logic developed on the CLP.

In order to preserve the flow measurement without the interference of the material's impact that is being reclaimed to the spear conveyor belt, the scale is mounted a reasonable distance from the bucket wheel, generally in the middle of the spear's conveyor belt. This distance of the scale to the bucket wheel causes an average delay of 10 seconds and for this reason the flow measured by the scale is not used as process variable.

3 STANDARD LOGIC FOR FLOW OPTIMIZATION

The standard logic for flow optimization existing on TMPM was developed aiming the control of the following variables:

- Rotation speed
- Translation step

3.1 Rotation Speed Control

3.1.1 Mathematic Data Modeling

Due to the high elevated delay of the bucket wheel in relation to the process scale according to figure 2, which prevents the deployment of a flow control, it was necessary develop a mathematic model to estimate the reclaiming flow and eliminate this delay, known as Dead Time (Smith, 1957; Astrom et al., 1994; Hagglund, 1992).

Initially was analyzed the correlation of the flow with the following process variables:

- Current or pressure of the bucket wheel.
- Current of the rotation engine.
- Rotation speed

It was noted the existence of a high correlation between the reclaiming flow and the current or pressure of the bucket wheel and low correlation in regards to the current and speed of the rotation. So, only the current or pressure of the bucket wheel was used for estimating the reclaiming flow.

In order to represent mathematically the estimated reclaiming flow it was used the ARX linear model which concepts are well demonstrated in Aguirre (2007) and the extended minimum square method (Aguirre, 2000) to estimate the parameters. In order to determine the order of the model the auto values analysis model, created by Lopes et al. (2010), was utilized.

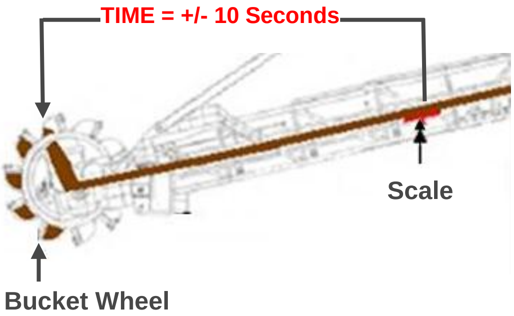

Figure 2: Delay between bucket wheel and the scale.

In order to estimate the parameters of the ARX model used data from current (input) and flow (output) as shown in figures 3 (current of the bucket wheel) and 4 (flow).

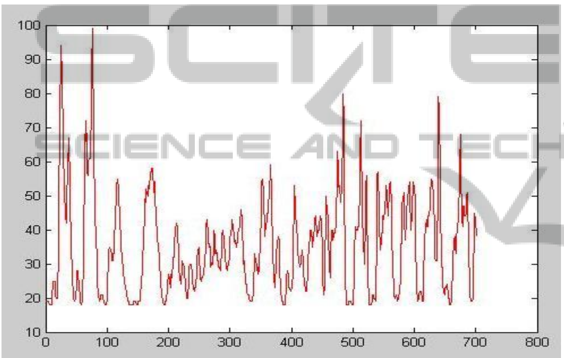

Figure 3: Data of current of the bucket wheel for estimating the model parameters (Axis x=number de samples / Axis y= current of the bucket wheel in Amper).

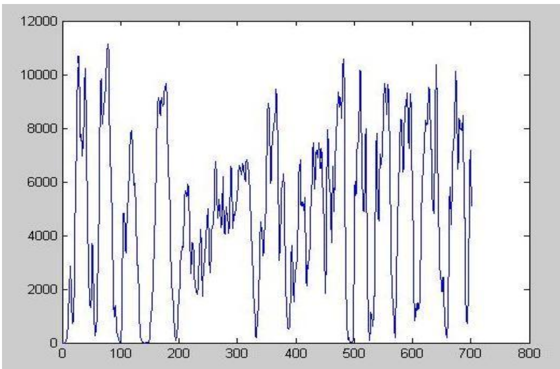

Figure 4: Data of flow for estimating the model parameters (Axis x=number de samples / Axis y= flow in Ton/h).

The 3° order model obtained was:

$$y(k) = 0{,}09y(k-3) - 0{,}76y(k-2) + 1{,}546y(k-1) + 12{,}11u(k-2) - 36{,}48u(k-1) + 43{,}238u(k) \quad (1)$$

For the model 1 validation it was used the data from the current of the bucket wheel and flow shown on the figures below.

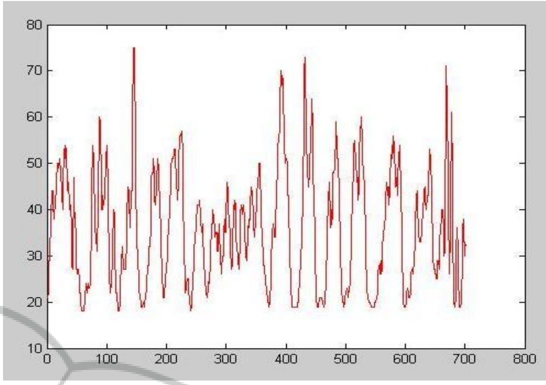

Figure 5: Data of current of the bucket wheel for validation of model 1 (Axis x=number de samples / Axis y= current of the bucket wheel in Amper).

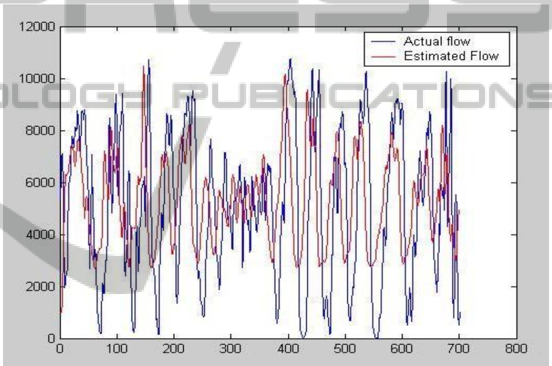

Figure 6: Comparison of actual flow with estimated (Axis x=number de samples / Axis y= flow in Ton/h).

The obtained flow and the estimated flow for current's data as seen on figure 5 are shown on figure 6. It can be noted that the estimated has a good representation of actual data.

3.1.2 Reinforcement Learning

Due to a change on the behavior of the current of the reclaimer's bucket wheel over time, the model 1 did not estimate the flow correctly any longer. The problem is verified a month after the system was modeled.

To fix this problem a new learning by reinforcement method was created called reinforcement by difference learning method and proportional reinforcement learning method. The procedure for utilizing this method is:

a. Analyze graphically the behavior of the real data with the data estimated by the mathematical model. Divide the graph in two or more areas, and these areas may be divided in accordance with a possible change in the behavior observed between actual and estimated data. On this work, it was divided in 3 areas: Area 1: Flow < 4000 t/h; Area 2: Flow >= 4000 t/h e <=8000 t/h; Area 3: Flow>8000 t/h.

b. Should the difference found between the actual and estimated data are just a stationary error choose the reinforcement by difference learning method. Should it is an error of proportionality use the proportional reinforcement learning method. On this work the reinforcement by difference learning method was used.

c. Should the reinforcement by difference learning method is opted, compare the delayed estimated data (according to the delay) with actual data, determine the difference between them (Actual data – Estimated data) and sum this difference to the estimated data. This difference should be calculated separately for each area determined on item a.

d. Should proportional reinforcement learning method is opted compare the delayed estimated data (according to the delay) with actual data, divide them (actual data / estimated data) and multiply the obtained value to the estimated value. This division should the calculated separately for each area determined on item a.

e. The calculation error between actual data and estimated data should be done every n seconds, being that the value of n will be determined according to the problem to solved. On this work it was used n=10 seconds.

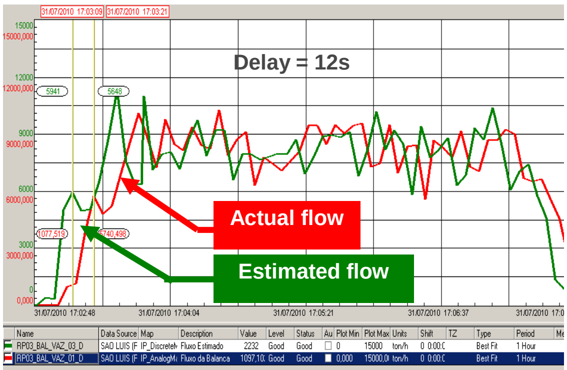

Figure 7: Estimated flow and actual flow comparison (Axis x=Time / Axis y= flow in Ton/h).

The model 1 and the reinforcement learning method was configured on the CLP of the reclaimer and at figure 7, data extracted from the PIMS, can be verified that the estimated flow has a good representation of the actual flow.

By the usage of the reinforcement by difference learning method on reclaimers and stackers-reclaimers of TMPM was possible to ensure accuracy of the estimated flow no matter the difference of the behavior of the bucket wheel over time. This accuracy can be verified on figure 8, 9 and 10 that during several months presented an estimated flow (blue) very close the actual flow (red) keeping the delay time.

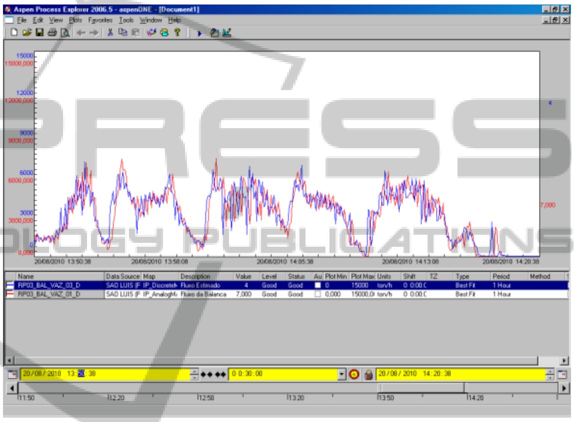

Figure 8: Comparison of actual flow and estimated flow on 08/20/2010 (Axis x = time / Axis y= flow in Ton/h).

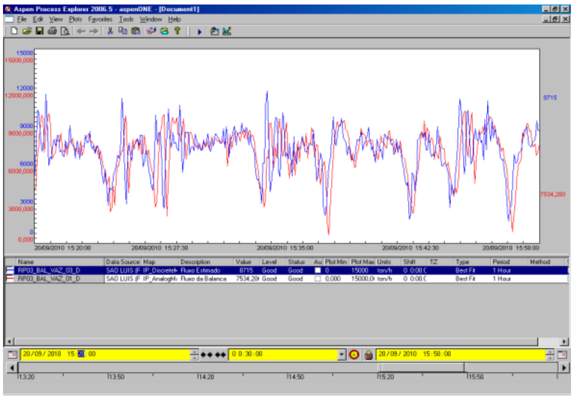

Figure 9: Comparison of actual flow and estimated flow on 09/20/2010 (Axis x = time / Axis y= flow in Ton/h).

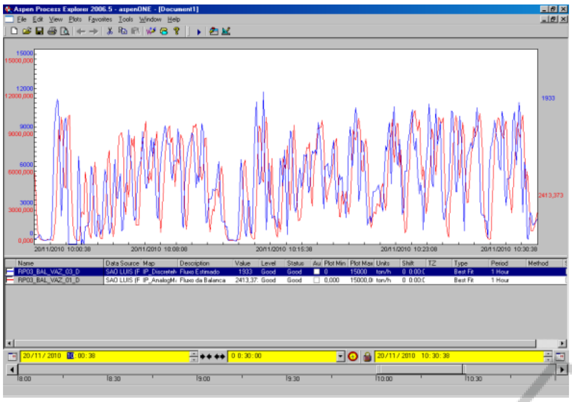

Figure 10: Comparison of actual flow and estimated flow on 11/20/2010 (Axis x = time / Axis y= flow in Ton/h).

3.1.3 PID Control

The rotation speed - which interferes on the intensity of the penetration of the bucket wheel in the pile – is defined through a PID control loop that has as set point (SP) the rate of the desired reclaiming flow and as process variable (PV) the estimated flow through the current of the bucket wheel's engine. The controlled variable (CV) is the Swing Speed Boom. The control loop can be verified on figure 11.

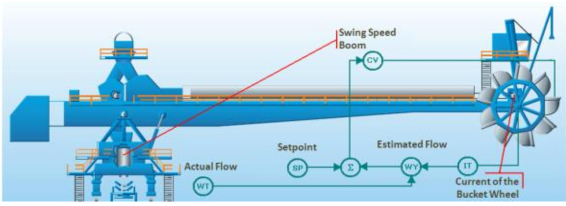

Figure 11: Control loop of the flow.

As the method for tuning the PID was not the purpose of this paper, it was used a practical tuning method and the parameters found were kp Gain = 0.3; ki Gain = 0.2; Sample Period = 100 milliseconds.

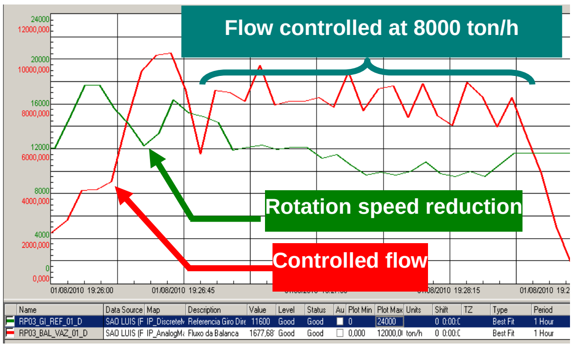

Figure 12: Flow controlled at 8000 ton/h (Axis x = time / Axis y= flow in Ton/h).

The PID control and the parameters found were deployed on CLP of the reclaimer and the result is demonstrated on figure 12 in which the operator has established as set point value of 8000 t/h and the PID controller adjusted the rotation speed until the desired flow has been reached. For this PID was setup a dead band of 500 t/h.

3.2 Translation Step

The initial translation step is manually defined by the operator and individually each direction for the rotation movement (clockwise and counter clock wise). Its adjustment is made according to time or distance for the translation in seconds or centimeters.

If the operator chooses the automatic control of the translation step, the ideal step is calculated according of the average rotation speed that the reclaimer needed to reach the setpoint value of the flow during one of the rotation direction. If the average speed of the rotation to achieve the desired flow is elevated the time or distance of the translation step is increase, if it is too low the time or distance of the translation step is reduced.

The higher the translation step the lower will be the rotation speed necessary for the reclaimer to reach the set point and smaller will the loses caused by the inversion of the rotation direction. On the other hand, higher will be the possibility of overflow occurrences and overloads on the bucket wheel. The lower the translation step the higher will be the rotation speed necessary for the reclaimer to achieve the set point causing more loses due to the inversion of the rotation direction. The idea is to adjust the translation step in order to make the desired flow to be achieved at a determined ideal speed in each rotation.

The logic for translation step control was configured on the CLP's reclaimer and the result is verified on figures 13 and 14. Before the implementation of translation step control the rotation in each direction, at base layer, has taken about 2 minutes, as shown on figure 13. After the implementation of the translation step control, the rotation in each direction, at base layer, turned out to take an average of 5 minutes, figure 14, reducing loses due to changes on the direction of the rotation and increasing productivity.

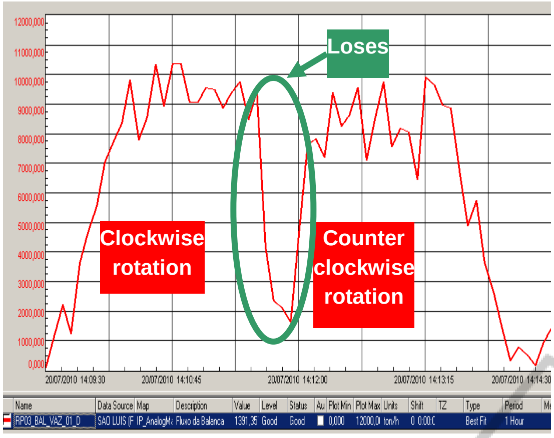

Figure 13: Time in each direction before implementation of the translation step control (Axis x = time / Axis y= flow in Ton/h).

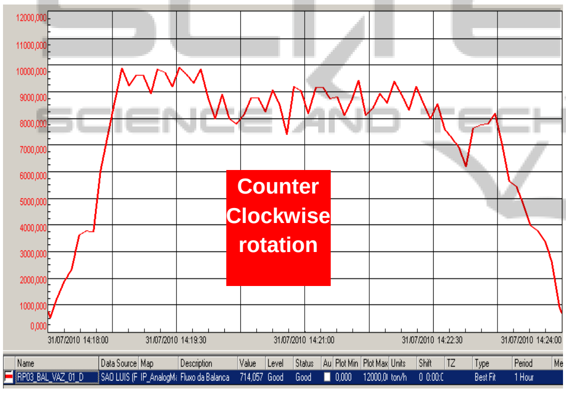

Figure 14: Time in each direction after implementation of the translation step control (Axis x = time / Axis y= flow in Ton/h).

4 OUTCOMES

The purpose of this paper for optimization of reclaimer flow control is the increase of productivity along with decrease of variability and overflow rates.

The variability or coefficient of variation (Cv) is calculated dividing the standard deviation (σ) by the flow average (μ):

$$Cv = \sigma / \mu \qquad (1)$$

At TMPM, overflow is considered as a reclaiming flow over 10,000t/h during a period higher or equals to 5 seconds.

In this paper will be demonstrated the results obtained with the deployment of the optimization work of flow control of the reclaimer RP-313K-03 and the Stacker-reclaimer ER-313K-04. The same work was developed for the other yard machines of TMPM and similar results were found.

4.1 RP-313K-03

On figures 15, 16 and 17 it is possible to notice that after the implementation of the flow control optimization for RP-313K-03 was obtained an average increase of 5% in productivity along with average reduction of 10% in variability and 20% on overflow occurrences.

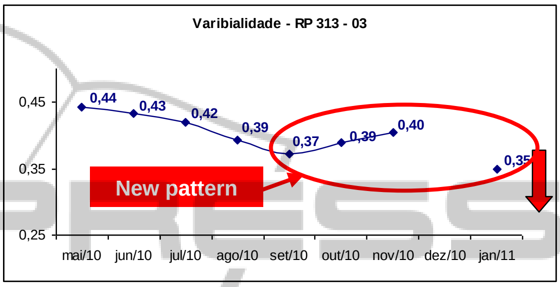

Figure 15: Variability evolution of RP-313K-03 (Axis x = time / Axis y= variability).

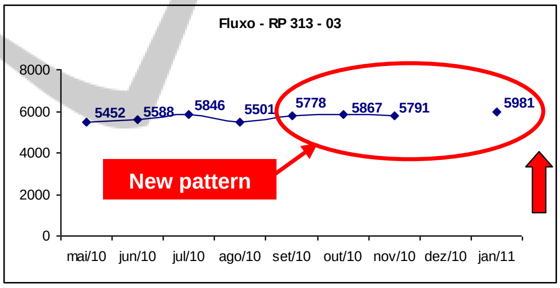

Figure 16: Flow evolution of RP-313K-03 (Axis x = time / Axis y= flow in Ton/h).

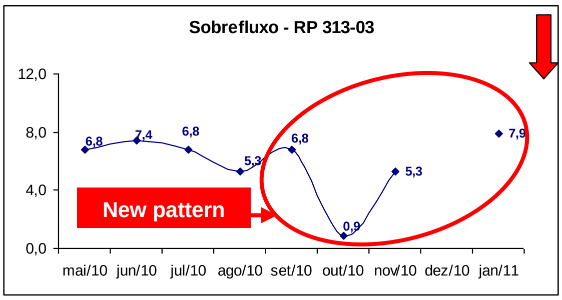

Figure 17: Overflow evolution of RP-313K-03 (Axis x = time / Axis y= overflow occurrences).

4.2 ER-313K-04

For the ER-313K-04 the result was even better, thus, as demonstrated on figures 18, 19 and 20 there was an average increase of 9% in productivity along with average reduction of 20% on variability and 39% on overflow occurrences.

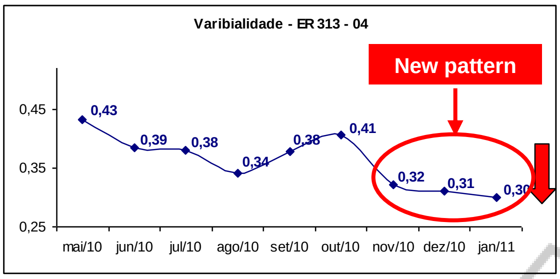

Figure 18: Variability evolution of ER-313K-04 (Axis x = time / Axis y= variability).

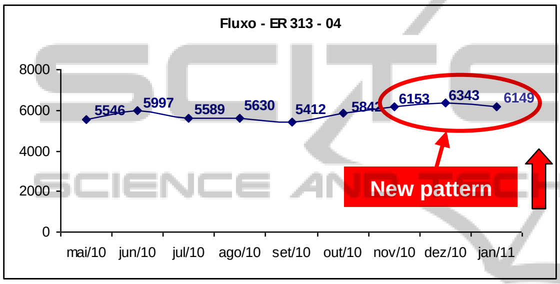

Figure 19: Flow evolution of ER-313K-04 (Axis x = time / Axis y= flow in Ton/h).

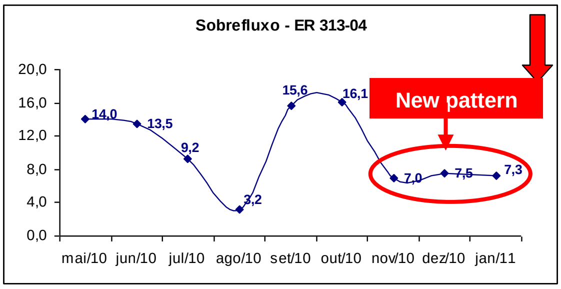

Figure 20: Overflow evolution of ER-313K-04 (Axis x = time / Axis y= overflow occurrences).

5 PREDICTIVE CONTROL

In order to improve the flow control in 2011 was developed a solution that is based on predictive control techniques (Camacho and Bordons, 1999).

To develop the predictive control, radar-like sensors were installed alongside the bucket wheel, as shown on figure 21.

Those sensors tell to the system the penetration distance of the bucket wheel into the pile and the height that is been reclaimed. By using this

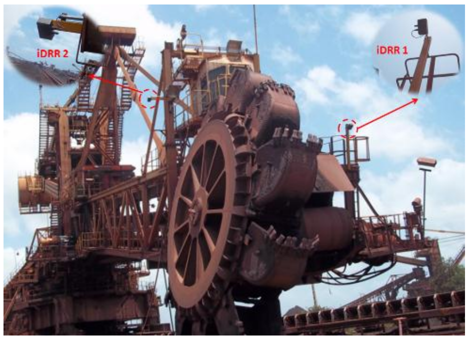

Figure 21: Radar-like sensors installation localization.

information along with the spin speed data it was possible to develop an estimator to predict the flow to be reclaimed. The comparison of the expected flow versus the actual one is shown on figure 22.

Figure 22: Comparison of actual flow (Green) and expected flow (Red) on 02/12/2011 (Axis x = time / Axis y= flow in Ton/h).

After the sensors were installed a logic was developed to verify the expected flow values and should it be higher or lower 15% of a desired flow a predictive control action is triggered, in other words, the PID flow controller is deactivated temporarily, the ideal speed reference calculated by the predictive control is written on the PLC and then the PID controller is reactivated. It is important to mention that the PID controls the flow that was estimated using the current or pressure of the bucket wheel as inputs. The action area covered by the controller is demonstrated on figure 23.

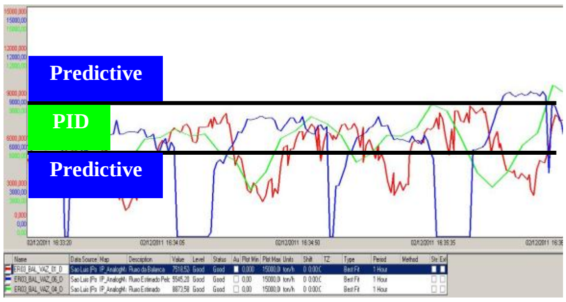

Figure 23: PID and Predictive control action area. Predicted flow (Blue). Estimated flow (Green) and Actual flow (Red). (Axis x = time / Axis y= flow in Ton/h).

The productivity gains with the implementation of the predictive control can be seen on figure 24 where area 1 represents the productivity values for the manual operation, area 2 represents the productivity values using only the PID control and area 3 represents the productivity obtained by using the predictive control. The improvements obtained are 11% over the manual operation and 6% over the isolated usage of the PID control.

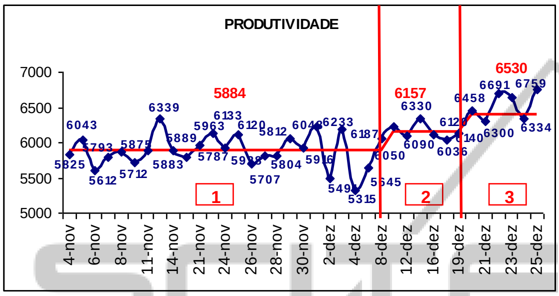

Figure 24: Productivity improvements with the utilization of the predictive controller. (Axis x = time / Axis y= flow in Ton/h).

6 CONCLUSIONS

The outcomes shown in this paper demonstrated that the new pattern adopted by Vale for the iron ore reclaiming process at TMPM, brought a significant increase of productivity for its operations. Additionally to the gain in productivity, it was possible to obtain a reduction in operational loses on the reclaiming process with reduction of overflow occurrence.

Due to the obtained gains, this new pattern for flow control developed at TMPM was established as a standard to be used by the other Vale's ports.

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