Real-Time Algorithm for Cone Crusher Control with Two Variables

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Abstract

Cone crushers are used in the mineral, mining, and aggregate industry for fragmentation of rock materials, minerals and ores. Systems used for controlling the Closed Side Setting (CSS) on cone crushers, and thereby the size reduction, are widely used to compensate for wear of the manganese crushing liners and to protect the machines from overloads. With a frequency converter also the eccentric speed in a cone crusher can be adjusted in real-time in addition to the CSS. The eccentric speed affects the dynamic interaction between the rock material and the crusher liners. Especially the number of compressions the material is exposed to is affected and also the local compression of the rock material is affected, thus the particle-size distribution of the product. Eccentric speed also affects crusher capacity. Real-time feedback data on the sellable product streams can be obtained by applying mass-flow sensors to the process. The adjustment of these two online parameters in real time can result in an increased potential for production yield; however, a nontrivial optimization problem with a large solution space also arises. As the feed material also varies, the optimal setting for the parameters varies in time.

Herein, we report the development of a monitoring and control system including a two-variable online algorithm for the selection of the setpoint for eccentric speed with respect to the current CSS. The different product yields from the crushing plant were monitored by mass-flow meters and continuously evaluated by a fitness function. A model for the outcome of the crushing stage, with the two parameters eccentric speed and CSS, was fitted mathematically to the measurement data. However, since the process varies continuously, due to the wear of crushers and screens and feed-material variations, the performance landscape is also continuously varying. Therefore, an Evolutionary Operation (EVOP) approach was adopted, wherein the variations are instead used to continuously find an operating point closest to the optimal.

The developed algorithm was tested and evolved at a crushing plant for aggregates that produces around 400 kton aggregates per year. The algorithm was implemented in a computer that communicated with the frequency converter and retrieved data from ten mass-flow meters in the process. The operator was able to interact and supervise the system through a HMI. The result is an algorithm that can determine the position and direction of a dynamic speed control to continuously improve the process-operation point. The magnitude of the improvement potential compared to a fixed-speed operation is from 5 to 20%.

Key words: crushing, process control, process optimization, eccentric speed, CSS
Introduction

Cone crushers are common production units used for size reduction of rock materials into finer fractions. Their main operating principle is the same today as when first developed over a century ago. A mantle rotates and moves eccentrically in the crushing chamber and the rock material is crushed between the mantle and the concave several times while falling downwards through the crusher. As the mantle and concave surfaces become worn, the distance between them must be adjusted to maintain the reduction ratio and control the top size of the product. This is done in one of two ways, depending on the crusher type. In the first type, the cone, on which the mantle is fixed, is vertically adjustable by a hydraulic system. The hydraulic system also serves as a safety system by dropping the cone to its lowest position if tramp iron comes into the chamber. Here, the concave is fixed in position. In the other type of cone crusher, the concave is attached to an upper part which has a thread on the outside, which allows the distance between the mantle and the concave to be vertically adjusted by turning the upper part. In this case, the mantle is fixed vertically. Both types of crusher can be equipped with an automatic control system that compensates for wear. Such a system helps the user to keep the size setting constant.

Another parameter of a cone crusher, the eccentric speed, has a great impact on the product properties. The speed affects the number of compressions that the material is exposed to and thus the particle-size distribution of the product. Similarly, the speed also indirectly affects the shape of the product. However, this issue is beyond the scope of this work. Capacity is also affected by the speed. Whereas changing the CSS moves the product cumulative particle-size-distribution curve horizontally, changing the eccentric speed tends to rotate it. The eccentric speed of a cone crusher can be changed by shifting pulleys on the belt drive. This is labor- and time-consuming, and is therefore not done unnecessarily. It is possible to adjust the speed continuously and more easily by applying a frequency converter. These have decreased in cost in recent years, making them more available for use in standard crushing applications.

Practical crushing operations encounter a wide range of variables: natural variations of the rock-material properties in the feed, wear of the equipment, weather, unwanted stops, etc. So, when implementing real-time control of a crushing plant, monitoring of the status of the actual process is crucial. It is difficult to measure product properties in real-time at a plant due to the high capacities, the dirty environment and the wide range of product sizes.

The purpose of a crushing plant is to produce rock material with certain properties rather than maintain a constant setting on the crushers. Therefore, from a user’s perspective of an optimal control system, the parameters to adjust should be the different sellable product capacities, i.e. size distribution and shape. Therefore, we herein propose an approach in which the properties of the crushing-plant products are the goal as the two variables described above are varied in concert. The inspiration comes from the factorial design of statistics.

The main focus of this work was the use of online product yields as measures of plant performance and the corresponding adjustment of the crusher control parameters. A standard conveyor-belt scale, for instance, can easily transmit information about the mass flow to a computer. Unfortunately, the cost of installing these is relatively expensive, leading to a very scarce usage in the aggregates industry. A more cost-effective way of measuring the current capacity is to measure the power draw on a conveyor belt that is performing a lifting work. Such a measurement device can be obtained for a tenth of the cost of a traditional belt scale. This principle is described by Hulthén and Evertsson in [5]. By directly measuring properties of the
sellable products after a screen, as shown in Figure 1, given that the quality aspects, e.g. shape, are acceptable, the control system (computer) is able to measure, and thus to control, the plant output particle-size distribution.

**Figure 1.** A mass-flow meter, e.g. a conveyor belt scale, is attached to each stream from the screen. The computer then estimates the particle-size distribution (PSD), seen in the box to the left. The above diagram is a real PSD and the “Time” arrow shows how the PSD changes to a coarser product as the mantle becomes worn.

**Earlier work**

In the 1970s, Karra performed a large number of tests on cone crushers with different parameter settings, including various eccentric speeds [8]. However, those tests showed no significant effects of changing the eccentric speed on the particle-size distribution, nor on the capacity. These results were later contradicted by the those reported by the authors, in more recent studies [6, 7]. The lack of observed effect in the older study may be attributable to any of a number of reasons, one being that the effects of other parameters were much larger. The lack of an accurate procedure for long-term evaluation is another explanation.

However, there are models where the eccentric speed affects both the particle-size distribution and the capacity, such as the work by Evertsson [2]. Nonetheless, studies on finding the best constant speed for cone crushers have been rare. Moreover, controlling the crusher continuously during operation is even rarer. To our knowledge, no study regarding online eccentric speed optimization has yet been published.

The authors previously showed that a crusher with an automatic-setting regulation can be improved by implementing a closed-loop feedback from the process; the improvement was 3.5%
In a following work, the authors implemented a real-time optimization of a cone crusher without a control system for CSS by instead controlling the eccentric speed dynamically. This improved the output from the crushing stage by 4.2%. It also increased liner lifetime dramatically with 27%. In a subsequent study, the setting and the eccentric speed parameters were combined and formed a model which predicts the output from the crushing stage. The model was then used in designing an algorithm which improved the process by 6.9%. However, this algorithm assumes that the constants of the model are kept updated. It cannot be assumed that the constants have the same values on other crushing stages, thus it must be re-fitted again and again.

Evolutionary operation (EVOP), as described in Box and Draper, is a method wherein the process variations are used for process improvements. If the process parameters do not vary, and they seldom are before EVOP is introduced, variations are purposefully introduced. The method is not an automated method, rather on the contrary; it is used manually in manufacturing and process industries. It can take several parameters into consideration, but these industries often have many to optimize, and the focus is normally therefore on which parameters to deal with. It is recommended that up to three parameters can be simultaneously used for optimization. The principle of climbing the “process mountain” is outlined in Figure 2.

![Fig. 2. The principle of Evolutionary Operation (EVOP). P is the original process point at which the optimization is started. The variables A and B are then varied in a pattern during the first phase. The levels of A and B for the next phase are decided upon the results from the current phase. The process performance is represented with elliptic altitude lines and the optimum is close to the common corner of phases 3 and 4.](image)

Holmes has successfully optimized a cement plant with an automatic EVOP system without any explicit model. The result was that the desired variable increased by 37% at the same time as the mixture of raw materials used was changed to a more profitable one. While a cement plant is
among the allied process industries, unlike crushing plants they have several parameters to vary in real-time.

Model

The models used in the real-time algorithm for CSS [4] and eccentric speed [6] both build upon the behavior of the process with a closed-loop return flow of the oversize particles. In the authors’ most recent study, it was clearly shown that a single fixed speed is not optimal over a short time frame [7]. The assumed appearance of the model is:

\[
\hat{y} = a + bx_1 + cx_2 + dx_1^2 + ex_2^2 + fx_1x_2
\]

Equation 1

where \( \hat{y} \) is the crushing-stage output (product yield), \( x_1 \) is the eccentric speed, \( x_2 \) is the time since the last CSS adjustment and \( a-f \) are constants; see Figure 3. In this work, the model in Equation 1 is applied, but the issue here is how to use it to improve a process automatically.

Algorithm

The challenge in this work was to fit the model described above and simultaneously use it for optimal crusher operation. Therefore, an EVOP approach was implemented on a Metso crusher from the Nordberg HP range (the latter of the two types described in the introduction). The CSS is adjusted regularly, but not dynamically, by a hydraulic motor, either on manual command or automatically. This is typically done every two or three hours of operation (this depends, of course, on the application). When the liners become worn the crusher must be empty of material before the CSS can be adjusted, because of the design of the crusher. The CSS is adjusted by stopping the feed, unclamping the thread, turning the top shell, clamping, and restarting the feed. This takes six to ten minutes before the process is up and running in steady-state mode again. Therefore, this adjustment can only be done, at most, a couple of times during a shift. Every operation time period between adjustments can therefore be defined as a run in an EVOP context.
Taking the model and the crusher-type limitations into consideration, three parameters have been resolved here:

1. Power draw when adjusted. If the power draw is high, the CSS is small. This implies high reduction but decreased capacity. A small CSS will also lead to a longer runtime before a new adjustment is needed.
2. Eccentric speed when the run is started, $n_0$.
3. Speed change, i.e. how much the eccentric speed should be changed, e.g. every ten minutes.

These three parameters are illustrated in Figure 4 and correspond to positioning of the model in x and y direction a rotation in the x-y-plane. Because Parameter 1 (Power Draw) is dependent on how much the gap is tightened, this was excluded as a controlling parameter in the EVOP algorithm.

![Figure 4. Parameters in the model correspond to positioning in two dimensions and one orientation of the model.](image)

The main reason why fixed settings are not optimal is that several factors in crushing plants vary with time. In addition to the short-term wear period of the crushing chamber discussed above, the factors that are beyond operator control are raw-material variation, screen-cloth wear, and total crushing-chamber wear over its useful lifetime.

**Full-scale tests**

**The plant and equipment**
The developed algorithms were tested at a crushing plant in Uddevalla, 80 km north of Gothenburg. The crushing plant is owned and operated by NCC Roads. The plant produces high-quality aggregate products ranging in size from 0–2 mm to 16–32 mm in its tertiary crushing
stage. The crusher is a Metso Nordberg HP4 equipped with a fine chamber. The feed size to this tertiary crushing stage is 16–70 mm. The crusher is equipped with a system for manual adjustment of the CSS.

The cone crusher was equipped with a Control Techniques Unidrive SP frequency converter, which allowed step less changes of the eccentric speed of the crusher in real-time. The pulleys were configured so that the nominal net frequency, 50 Hz, which then corresponds to 1500 rpm on the motor would give 952 rpm on the crusher’s drive shaft.

After the crusher, a series of two classifying screens sort the product into size fractions of 0–2 mm, 2–5 mm, 5–8 mm, 8–11 mm, 11–16 mm, 16–22 mm and +22 mm. The +22 mm material is always returned to the crusher in a closed circuit. All products at sizes of 5 mm and larger can be returned in a closed circuit at 0, 50 or 100% re-crushing rates. During the final test runs, 100% of the 8-11 mm product was re-circulated back to the crusher.

An outline of the plant is shown in Figure 5. In total, ten conveyor belts had mass-flow meters monitoring the electrical power draw. The power was measured with power transducers, which can deliver real-time information to a computer, where the actual capacities are calculated.

![Figure 5. Tertiary crushing stage at NCC Roads' plant in Uddevalla. The plant produces six profitable products from the tertiary stage. The oversize particles are re-circulated to the crusher.]

The algorithm was implemented in a computer that communicated with the frequency converter, retrieved data from ten mass-flow meters in the process, and also interacted with the operator. In addition to this, an HMI/Scada system was developed for communication with users, see Figure 6. Using the ten mass-flow sensors, all material flows can be monitored by the operators in real-time.

The adjustments of the eccentric speed were performed automatically, both during each run and to a new value before starting the next run. The CSS was measured indirectly from the power draw. While the power draw cannot be controlled accurately, the level of CSS adjustment is roughly reflected by the power draw. Therefore, the desired power draw was provided to the operator on the HMI. The performance of the plant is here defined as the net crushing-stage throughput, i.e. the crusher throughput minus the circulating load.
Test period
The initial experiments were conducted during 2009. The implementation and tests of the new algorithm described above were conducted between March 23rd, 2010 and July 12th, 2010. Phases I through IV occurred during March 23rd–April 29th, April 30th–May 11th, May 20th–June 9th, June 18th–July 12th, respectively. During this period, all operation of the crushing stage was recorded. On March 23rd, the set of liners were about 20% worn. A change of liners took place on June 14th, between Phases III and IV. A period constant operation at 52 Hz took place between Phases II and III. Every run between two CSS adjustments was recorded, and a performance value (mean), the standard deviation, and the length of the run were calculated. The decision when to adjust the CSS was mostly due to the fact that the power value went below a stated limit, 200 kW, but there were also other reasons, e.g. shut-down time, tramp, or lack of feed material. This time varied greatly, from a couple of minutes to three hours or more. The shortest time corresponds to repeated adjustments of the CSS, while the longest corresponds to times when the operator was too busy with other maintenance. An economical optimum is calculated to between one and two hours. Therefore, a time of 5,000 seconds was chosen as the period for which performances were compared, regardless of whether or not a run was continued for a much longer time; runs of less than 5,000 seconds were neglected.
## Results

The EVOP was run in five phases. The result of the EVOP runs can be seen in Table 1. The center point in each phase is denoted by ‘P’ in Figure 2. The parameters were varied around this point.

### Table 1. The EVOP runs and their results.

<table>
<thead>
<tr>
<th>Run</th>
<th>Parameter 2 Start speed [Hz]</th>
<th>Parameter 3 Speed change [Hz/h]</th>
<th>Average performance after 5,000 s [tph]</th>
<th>Change compared to center point</th>
<th>Average power draw [kW]</th>
<th>Maximum power draw [kW]</th>
</tr>
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<tbody>
<tr>
<td>Original settings</td>
<td>50</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Optimal settings according to [7]</td>
<td>42</td>
<td>2.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tested setting in [7]</td>
<td>42</td>
<td>2.25</td>
<td>274</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Phase I Center point</td>
<td>0</td>
<td>47</td>
<td>3</td>
<td>183</td>
<td>151</td>
<td>216</td>
</tr>
<tr>
<td>Phase I</td>
<td>1</td>
<td>49</td>
<td>4.5</td>
<td>151</td>
<td>-17%</td>
<td>148</td>
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<tr>
<td>Phase II Center point</td>
<td>0</td>
<td>46</td>
<td>1.3</td>
<td>199</td>
<td>162</td>
<td>240</td>
</tr>
<tr>
<td>Phase II</td>
<td>1</td>
<td>48</td>
<td>3</td>
<td>172</td>
<td>-13%</td>
<td>149</td>
</tr>
<tr>
<td>Phase III Center point</td>
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<td>45</td>
<td>0.7</td>
<td>165</td>
<td>144</td>
<td>230</td>
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<tr>
<td>Phase III</td>
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<td>47</td>
<td>1.3</td>
<td>128</td>
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<td>121</td>
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<td>Phase IV Center point</td>
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<td>0.8</td>
<td>170</td>
<td>148</td>
<td>220</td>
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<tr>
<td>Phase IV</td>
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<td>1.6</td>
<td>130</td>
<td>-23%</td>
<td>118</td>
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<tr>
<td>Phase IV</td>
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<td>47</td>
<td>0</td>
<td>182</td>
<td>7%</td>
<td>158</td>
</tr>
<tr>
<td>Phase IV</td>
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<td>44</td>
<td>0</td>
<td>192</td>
<td>13%</td>
<td>169</td>
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<tr>
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<td>44</td>
<td>1.6</td>
<td>163</td>
<td>-4%</td>
<td>138</td>
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</table>
**Discussion**

The standard deviations during the runs were relatively high, on average 14% of the measured values. Box and Draper, however, state that large experimental error often indicates a lucrative source of improvement and it is probable that larges effects can be detected [1]. Note that the improvements according to the EVOP results shown in Table 1 are often of the same magnitude.

The correlation coefficient between the average power draw and the performance value is 0.845, which clearly indicates a link in the form of the amount of size reduction achieved. However, the correlation coefficient between the maximum power draw and the performance value was only 0.588, which is low.

It is clear that these results show a huge potential for working actively with the speed. The differences between the worst and best runs were 30%, 29%, 23% and 36% in Phases I-IV respectively. The performance values varied even more over the entire crushing-chamber lifetime, as can be seen in Figure 7. The differences were systematically more than 100 tph. This is also in accordance with our prior findings and at the same time underlines the importance of measurement over a longer period of time [6]. It is also clear from Figure 7 that individual runs cannot be compared with runs from other phases. The differences observed during the service lifetime of a set of liners underscores the fact that the operating conditions vary, and therefore different speed strategies should be investigated.

*Figure 7. The performance varies greatly during the service lifetime of HP-crusher liners.*
A clear path for the EVOP-algorithm is towards lower speeds (Parameter 2) and smaller speed changes (Parameter 3). In Phase I, and perhaps Phase II, this was expected. However, in Phase III the EVOP continues to point in a downward direction in both speed and speed change. The same pattern was seen in Phase IV, although the liners were changed here. To understand this, new adaptations of the models were made from data collected during the EVOP tests. The results, as shown in Figure 8, were that all runs were performed at higher speeds than the model optimum. The EVOP algorithm has clearly pointed out the direction for the dynamic optimal speed. In comparison with the earlier algorithm, Finite State Machine (FSM), the EVOP algorithm is less sensitive to noise. However, it cannot react to short-term variations, e.g. changes in raw-material properties.

When lowering the eccentric speed of an HP-crusher, the electric-power demand normally increases. This is evident by inspection of the maximum power draw in Table 1. HP crushers are known for stalling when too heavily loaded. Stalling occurs when the crusher takes in more material than it can handle, and it simply stops and the top shell starts to float with the chamber full of material because of overloading of the pretension hydraulics. This is the reason why the continued lowering of the speed was not explored; because the EVOP is programmed in an automatic script which interacts with the crusher automatically, no risk for overloading the crusher could be taken. Future work will include manually testing several runs around the optimum settings.
Conclusions
An inevitable development in the rock-crushing industry, especially the aggregate industry, is a more process-oriented focus where new and more cost-effective measuring methods will be introduced. The monitoring will be done on both production equipment and product yields. In this study, a two-variable algorithm utilizing a previously developed model was tested for continuously improving the process-operation point. The level of improvement in each phase was in the region of 15%.

With an algorithm that automatically chooses the set-point values, crusher operation requires less attention from the operators. In addition, when given more instruments, such as a graphical user interface on the control computer, the operators’ handling of the plant will subsequently improve. There are also great improvement possibilities in adjusting the liners at the right time, which good instrumentation can facilitate. Also, the time at which the liners are replaced should be further investigated. It remains an open question if it is acceptable that the liners can sustain an almost 50% systematic performance decrease, which has been seen in several currently operating crushers and confirmed by talking with people well-grounded in the field.

The EVOP algorithm clearly pointed out the direction for the dynamic optimal speed. Compared with earlier algorithms, this EVOP algorithm is less noise sensitive. However, it cannot react to short-term variations, e.g. changes in the raw material feed.

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