CRUSHING PLANT PROCESS OPTIMISATION

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ABSTRACT

Design of processes in order to find the most efficient solution to a specific task is a difficult problem. Often the number of solutions are large and the optimal solution is therefore difficult to identify. Crushing plant process design is no exception from this statement. In order to find the best solution issues like equipment selection and process configuration must be mastered. The solution must both be technically feasible and preferably have a low operating cost. Since crushing plant design is a complex task with a large solution space it is basically impossible to master without a specialised tool. For a long time simulation softwares have been used to assist in the design process. These tools only give answers for how a user defined plant will operate. There are no tools with capabilities to consider different design options in order to determine what the most efficient solution looks like.

In this paper a method for crushing plant design optimisation is presented. The novel method utilises a combined optimisation routine and expert system in order to find the most cost efficient solution to a given process task. The user will only need to define the feed material properties, the process capacity, and the end product requirements. The developed system will find the solution lowest production cost per ton.

Keywords: optimisation, expert system, simulation, crushing plant

INTRODUCTION

Crushing and screening processes design is a complex and multi disciplinary task. A process can be configured in many ways in order to fulfil the same task. The question then quickly arise: What is the most cost efficient way to produce the needed end product? The solution space for this problem is normally very big and contains variables ranging from crushing stage and equipment selection to operating parameter determination.

The purpose of the research presented in this paper is to explore the process design of crushing plants in order to gain further understanding on how the crushing plant process can be made more optimised.

Earlier work by the author has focused on optimisation on existing plants (Svedensten, 2007). This work together with studies by others on similar industrial processes has shown that in order to optimise a process three main areas need to be covered (Montgomery, 1996):

- Structure - Plant layout and production unit selection
- Parameters - Set up of the variable parameters in the production units
- Tolerances – Allowed variations of the parameter values.

Since the previous studies focused on existing plants *Structure* were always excused since it was given by the initial condition of the problem. In order to make a full process optimisation all three areas should be included in the optimisation. Optimising all three areas at once is a very big problem to handle and can not be solved within reasonable time on a normal computer though. For the current research it was therefore decided to exclude *Tolerances* from the problem and focus on making combined optimisations of *Structure* and *Parameters*.

Work in this area has previously been made by Huband *et al* (2006). Their work had a somewhat more basic approach to circuit design. For each stage there were only two options with regards to configuration: Open or closed circuit. That is not sufficient since there are many types of open and closed circuits and they will all have different performance. This work has for example identified four different types of open circuits that all must be a part of the solution space, see figure 1. The same

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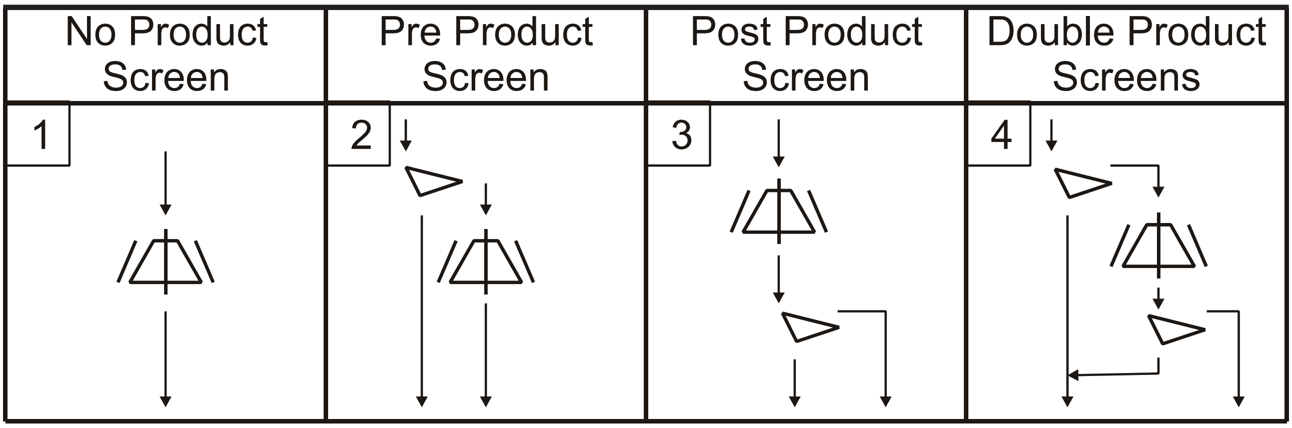

FIG 1 - Four different types of open circuit crushing stages.

goes for closed circuits, there are many more closed circuits then just the basic crusher followed by a screen and recirculation of the over size. In addition to single machines in the stage parallel units must also be considered in order to reach the desired capacity.

The paper has the following outline. It starts by describing the main design idea of crushing and screening plants. It is important to understand the purposes of the different crushing stages in a crushing plant. By knowing the purpose of the different stages the optimisation can be made more efficient and only include the necessary parts of the process. In order to predict the performance of the crushing plant a modelling and simulation system is used, this is briefly described followed by a description on the combined optimisation routine and expert system. It is the combined routines that enable the problem to be solved efficiently. For the optimisation of the system a cost function is used to evaluate proposed solutions.

Finally an example has been made to demonstrate the capabilities of the new system. This is followed by the results and future work

CRUSHING PLANT PROCESS DESIGN

The crushing and screening process are normally divided into different stages. Each stage has the purpose of size reduction and often also classification. The configuration of a crushing stage varies depending on where in the process it is located and what task it is aimed to perform. One can also quickly make a diversion between the primary crushing stage and the following stages.

Primary crushing stage

The task of the primary stage is mostly feed material preparation for further processing. The design of the primary stage normally has the following purposes:

- Even out the flow rate of material being delivered to the plant by the trucks.
- Remove unwanted material like dirt.
- Reduce the material to a size that can be processed by the following equipment.

The purpose of the primary stage is not very much involved in the actual process since its main tasks are material preparation. The actual processing of the material must therefore be sad to start after the primary stage. The design of the primary stage therefore mainly aims at handling the above issues and to ensure that the rest of the process will have the needed conditions for further processing.

Following crushing stages

After the primary stage an intermediate buffer is normally used. This buffer has the purpose to feed the rest of the process with an even stream of material. It is important for the process that material can be provided at a given rate. This ensures that the process will be as stable as possible. Since plants often have a lot of conveyors that from a process point of view acts as time constants it is important to keep the process well balanced.

One of the fundamentals of crushing stage design is to use either *Open Circuit* or *Closed Circuit*. The definition are as follows: *Open Circuit* is defined as a combination of a crusher and one or more screens configured in a way that only allows all or parts of the material to pass the crusher once.

Closed Circuit is defined as a combination of a crusher and one or more screens were all or parts of the material will pass the crusher. Over sized material will then be re-circulated to somewhere before the crusher and thereby fed to the crusher again to be re-crushed. Parts of the rock material will thereby pass the crusher more then once. The two types of stages have some fundamental differences that affect the design of the crushing plant both in terms of technical performance and cost of operation. The crushing stage design will for example affect aspects such as: Equipment size, number of equipment, reduction ratio, build complexity, wear part consumption, final product extraction possibilities, product quality, and so on. In addition to this the design of the crushing stage will also put demands on the surrounding crushing stages. Making one crushing stage simple and thereby with a low cost might increase the complexity of a neighbouring crushing stage. For example the production of a certain product might need three crushing stages if two open circuits and one closed circuit are used. The same task might be possible to accomplish using two closed circuits. The one to select must therefore be evaluated in order to find the best technical and economic solution. It is therefore important to be able to evaluate different configuration against each other. The normal procedure is to use simulation software and evaluate different concept in order to find the best one.

There are no given rules on how to combine crushing stages. In mining applications it is common to start by open circuits and finish with a closed circuit. There are many other configurations though. The general idea is often to screen out the finished product at one point in the crushing stage and send the oversized material to the following stage. The final stage must always process all of the incoming material to finished product though.

MODELLING AND SIMULATION

Modelling of crushing and screening processes is normally done by combining models of the equipment sub processes. The models are connected together to from a process model. This means that in the grid of models results from one model is input to another one. Apart from reacting to the feed material properties most of the units in the plant will also allow for changes to be made to them. This ranges from equipment selection to selection of operating parameters like for example Closed Side Setting (CSS) and Eccentric Throw (ECC) on crushers and separation size on screens.

Simulation of crushing plants is often performed with steady state simulation. There are two main reasons for using steady state simulation: It utilises a limited amount of CPU power and it gives a prediction of the long term performance of the plant. Using dynamic simulation of crushing plants will also need a lot more information then what normally is available at the design phase of the crushing plant construction. A steady state simulation of a crushing plant begins with the feed unit model's output being fed to the first production unit model in the flow sheet. The output and performance of the first production unit model are then calculated. The output is fed to the following production unit model, after which the output and performance are calculated. This process of transferring information between the production unit models is repeated until all production unit models have been calculated once. It then starts all over again with the feed unit models. The whole process is repeated until equilibrium has been reached.

OPTIMISATION TASK

As stated in the introduction the purpose of the research was to find a method to find the best process for a certain task. Since this is such a big problem with many dimensions computer optimisation must be used. The optimisation routine operates together with the simulation routine with the purpose to generate different solutions that are evaluated using the simulation routine. In order to make this evaluation the result a cost function is used. At the start of the work it was quite quickly discovered that only having an optimisation routine that freely combined equipment and operating parameters to arbitrary plants is very inefficient. Almost all solutions proposed by the optimisation algorithm can easily be determined as unfeasible. Simulating the performance of the unfeasible solutions wastes a lot of time and must therefore be prevented. In order to solve this a set of design rules must be used that eliminates the unfeasible solutions. These design rules are well known to the design engineer and used during normal design of crushing plants. It can for example be what combinations of closed side settings and separations that can be used in closed circuits or rules on how screens and crushers can be combined. In order to assist the optimisation routine the design rules have been implemented in an expert system.

Expert system

During optimisation the optimisation routine runs together with the expert system. The expert system has three main tasks:

- It has information on how equipment should be configured.
- It runs checks on the solutions on the purposed by the optimisation routine and determines if the solution should be simulated.
- The expert system also determines the value on some of the optimisation parameters.

The configuration system in the expert system basically has different types of allowable combinations of machines coded. This reduces the number of combinations the optimisation routine can evaluate. Basically all types of closed and open circuits can be used by the optimisation routine, anything else is prevented. By having a diverse library of feasible crushing stages coded into the expert system it still allows for a large number of possible combinations but eliminates solutions that are totally unrealistic.

After the expert system and optimisation routine have found a configuration of crushers and screens that are allowed a second test is made. Even though all parts of the proposed solution are feasible they might not be feasible to use together. Example of this is one stage ending with a screen separating the final product and the next stage starting with a screen doing the same task. Another example is one crusher directly feeding the next without having a screen in between. Solutions like these will generate a result if simulated but should still not be considered as valid.

During optimisation of a given plant some parameters does not need to be determined by the optimisation routine. In this work parameters such as equipment sizing and configuration can be partly made by the expert system. By utilising information about the properties and amount of feed material to a machine it can be configured so that it will have the needed capacity. This eliminates the need for the optimisation routine to find the equipment. Another example of parameter selection made by the expert system is for screens. Depending on the purpose of the screen deck can either be for process of final product separation. If the purpose is for process the separation size must be determined by the optimisation routine, if the purpose is to generate a product the separation size can be determined by using the product requirement. The expert system therefore has a feature to determine the purpose of all screen decks in the process.

For the remaining parameters that cannot be determined by the expert system the optimisation routine is used.

Optimisation cost function

The purpose of the crushing and screening plant is to produce the desired product at the needed production rate with the lowest possible cost. This is formulated as minimising the cost per ton finished product. It is important to formulate the cost function correctly otherwise the optimisation routine will not deliver the desired result.

In order to calculate the cost per ton the following costs are included: Equipment depreciation, equipment service, equipment wear part replacement, losses due to unavailability during maintenance and energy cost.

Optimisation routine

The objective of the optimisation is to minimise the calculated cost per ton. Since the solution space is big it is very difficult to find the optimal solution manually. The need for computerised optimisation method is therefore imminent. The selected optimisation routine is Probabilistic Global Search Lausanne (PGSL). It is a discrete optimisation method that has shown to be very powerful for solving these types of problems (Svedensten, 2007).

According to Raphael and Smith (2003) PGSL has a short CPU time and equal or better probability of finding the global optimum then a normal genetic algorithm. This is also confirmed by the testing done during earlier parts of the research project. It is also well suited for direct implementation in optimisation software, being very flexible when it comes to the number of parameters and no need for initial guess. PGSL is based on probability distributions of the different discrete values that a parameter can take. This probability distribution is used for generating new combinations of parameter values. Intervals around parameter values that generate the best values of the cost function results are given an increased probability of selection. New values are generated many times and the probability distribution is constantly updated. During the process the interval around the best value is narrowed and the probability of selecting values in the interval is increased.

EXAMPLE

In order to illustrate the capabilities of the developed routines a small example has been constructed. The task is to process an ore to a mill feed smaller then 15mm, P80<12 mm. The ore has a bulk density of 1.6 tones per cubic meter, has a Bond work crushing index of 16 and an Abrasive index of 0.5. The production rate is 1200 tph. As stated above the primary stage is not a process part in its true sense since it is more of a preparation stage for the rest of the process. The primary stage has therefore been designed manually to handle the incoming trucks from the pit. The feed material to the process is therefore a primary crushed material smaller then 350 mm. The crushers that the optimisation rouitine are allowed to select from are Sandvik CH cone crusher, ranging from the smallest CH420 to the biggest CH880. The chamber design ranges from Extra Coarse (EC) to Extra Fine (EF). The screen possible for selection is the Sandvik LF range of screens. Basically the screens have been selected by the expert system in order to find correct area load, not exceed the carry over capacity and keep the bed depth within defined levels.

The optimisation task was to find the most cost efficient solution, it were allowed to design anything between a two stage plant and a four stage plant. The optimisation routine needed approximately 6 hours to complete the task. The computer used for the optimisation was an IBM laptop that has a 2.4 GHz Intel CPU.

The optimisation resulted in a wining solution; this is presented together with the four runner ups in figure 2 and table 1. In addition to the best solution it is interesting to see the diversity and similarities of the runner up solutions.

It can be see that all of the top five solutions were four stages (primary stage not shown). The first three stage solution was rated outside the top ten. During the optimisation it was actually surprising to see how low the three stage solutions was rated. One would expect that these solutions are lean on equipment and thereby operating cost but so was obviously not the case. Instead it is likely that the

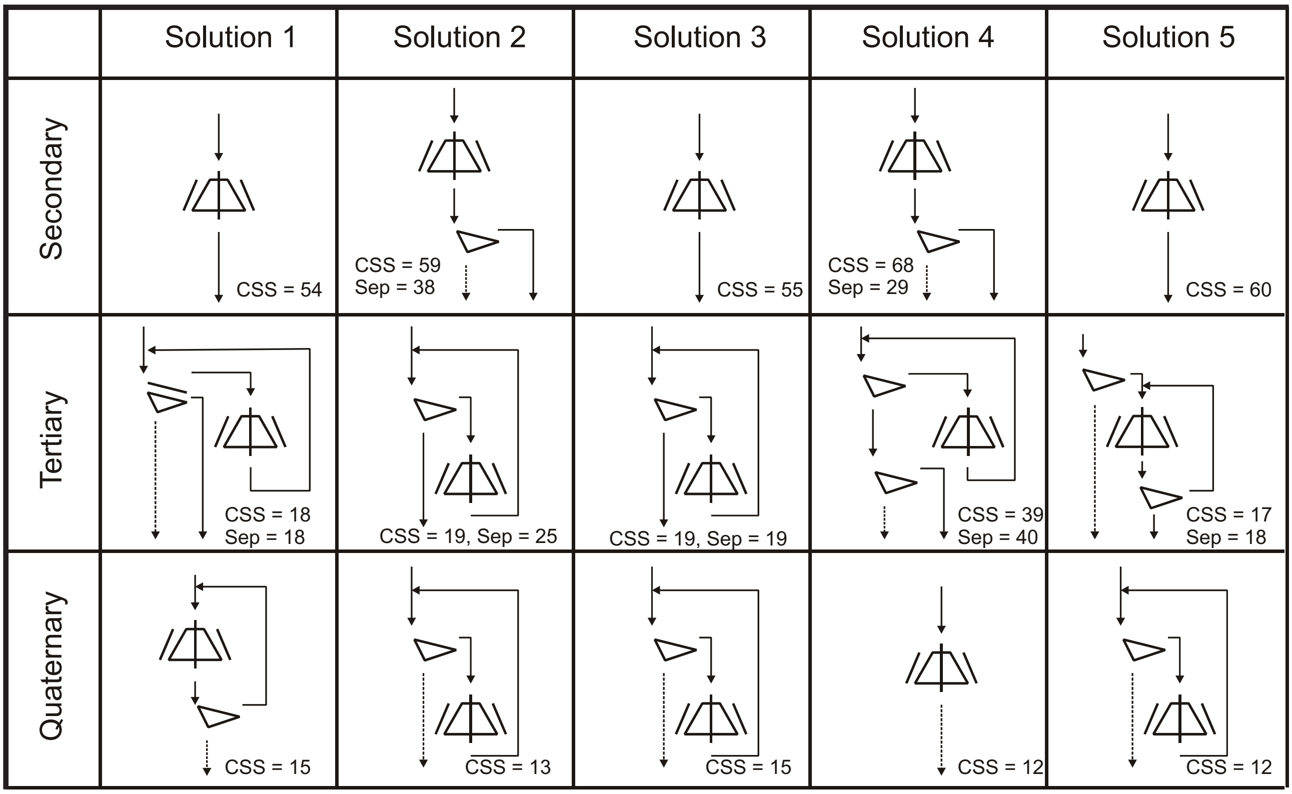

FIG 2 - the top five solutions to the optimisation problem. The dotted lines shows finished product. The noted separation size is for the process screening. For product screening the separation size is 15 mm. All numbers in the figure are millimetres.

TABLE 1

Result in details from the top five solutions to the optimisation problem.

	Optimisation Solution	1	2	3	4	5
	Total cost per ton	0.94 €	1.02€	1.03€	1.07€	1.11€
Stage 1	Selected Crusher	1x CH880EC	1x CH880EC	1x CH880EC	1x CH880EC	1x CH880EC
	Crusher ECC and CSS	ECC 26 mm, CSS 54 mm	ECC 32 mm, CSS 59 mm	ECC 36 mm, CSS 55 mm	ECC 58 mm, CSS 68 mm	ECC 32 mm, CSS 60 mm
	Selected Screen(s)	---	4x LF1030D	---	4x 1030D	---
	Process Separation	---	38 mm	---	26 mm	---
Stage 2	Selected Crusher	3x CH870EF	2x CH870EF	3x CH870EF	3x CH870EF	3x CH870EF
	Crusher ECC and CSS	ECC 57 mm, CSS 18 mm	ECC 68 mm, CSS 19 mm	ECC 57 mm, CSS 19 mm	ECC 57 mm, CSS 18 mm	ECC 57 mm, CSS 17 mm
	Selected Screen(s)	5x LF2470D	3x LF1850D	4x LF1850D	5x LF2470D	4x LF1850D 4x LF2770D
	Process Separation	18 mm	25 mm	19 mm	18 mm	18 mm
Stage 3	Selected Crusher	CH660 EF	1x CH870EF	CH660EF	1x CH660EF	1x CH660EF
	Crusher ECC and CSS	ECC 40 mm CSS 15 mm	ECC 80 mm CSS 13 mm	ECC 50 mm CSS 15 mm	ECC 40 mm CSS 12 mm	ECC 32 mm CSS 12 mm
	Selected Screen(s)	LF2160D	2x LF2770D	4x LF2770D	---	LF1230S
	Process Separation	---	---	---	---	---

three stage solution needed many parallel units in closed circuit to be able to process the material with a high reduction ratio.

Regarding the screen selection it can be seen that it sometimes matches the number of crusher somewhat poorly. In order to correct this manual correction is needed by fine tuning relieving decks and/or process separations.

Regarding the equipment selection the routine have found the CH880 EC to be optimal for all secondary stages. This machine is needed to handle the material being produced by the primary crusher. Due to its large capacity the routine has not found it beneficial to screen of any material before the crusher and neither to configure the secondary stage as a closed circuit.

For the secondary stage the a few different solutions have been proposed. They all are similar in the sense that they all use screens in front of the crusher. By adding a screen in front of the crusher the needed crusher capacity is reduced. For the final stage different solutions are again proposed. Depending on the performance of the previous stages either closed or open circuits are used.

RESULTS

This work has resulted in a new method for optimising crushing plant processes. This work brings a new dimension to the earlier work done by the author were only existing plants were subject for optimisation. The new method finds the best crushing plant process that takes the given feed material and makes it into the desired end product. The proposed solution by the optimisation algorithm is the most cost efficient way to realise the needed process. The work has not the intension to replace the design engineer in any way. He will still be needed, instead the work should be viewed as tool to make the process easier. The proposed solution are good starting points for the design work since it only looks at the problem from a process point of view. Often there are also practical issues that need to be taken into account as well when processes are designed.

FUTURE WORK

The results from this work will also be used to study different cases in order to investigate if any general recommendations on crushing plant process design can be found. There might be crushing stages or combination of crushing stages that shows to have great representation in wining solutions for certain problems. If that is the case that type of solution could be developed into standardised solution that can be used on a regular basic.

The developed method also only applies on crushing plants in mining application. In order to widen the usage aggregates production should be included in the expert system. Aggregates production have more types of crushing stages configuration that needs to be explored and the quality demands are also more complex since particle shape often is involved.

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