

COST ANALYSIS FOR CRUSHING & SCREENING: DEVELOPMENT OF A METHODOLOGY FOR DETERMINATION OF PRODUCTION COST FOR PRODUCT FRACTIONS

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Abstract: The comminution processes are complex and there has thus far been no, previously published, efficient way to calculate the cost per product and metric ton. The proposed model has been adapted to fit the currently investigated process of crushing and screening (C&S). Deriving from the original model, the proposed new model is presenting the result in cost per metric ton of raw material. It has been indicated to be a useful approach for calculation of the production cost and deciding the profitability of a product on a more detailed scale, in the comminution industry.

Keywords: Comminution, crushing, screening, production cost, mineral fractions

1. INTRODUCTION

The mining and construction industry is a huge, global one and accounts for 6 to 7 % of the world's total energy consumption (Manoucheri). The turnovers are large and the market price of some minerals has risen with over 500 % in ten years. The market has grown but the competition among producers has become more present. This along with a future predicted decline in market price set high demand on the producers and the old fashioned mind-set of the industry could very much use change to a different approach from the current one. An introduction to a new way of distributing costs will present opportunities to make operations more efficient and through that find new ways of linking technology and economics. The connection between technology and economics, represented by the production-economic model (Ståhl, 2013) by Ståhl, is the foundation of the production philosophy *NEXT STEP*.

To this day there is no previously published way to calculate the production cost for mineral fractions, per metric ton, in a good way. Attempts have been made but the results often come down to the difficulty in deciding all the in-data (Svedensten, 2007) in correct ways and focus has then been shifted to user friendliness. Due to the importance of correct in-data for a satisfactory result a lot of effort, except for the actual adaptation of the production-economic model to current application, has been put on validation of in-data. Mining and construction processes contain several different operations and parameters with great complexity (Sandvik Rock Processing Manual, 2011) and it is therefore difficult to attain viable results. The objective is to develop a new production cost model for the comminution industry and specific crushing & screening (C&S). The model aims to present more accurate results when calculating the production costs and a tool for cutting costs and optimizing processes. The model is to be applicable to different sites and setups and the possibility exist to expand the boundaries to include more processes in comminution.

2. METHODOLOGY

2.1. Work steps

The project methodology was created early on for the development and adaption of the new proposed production cost model. The following steps were gone through to complete the project:

1. Mapping of process-flow for a whole C&S plant.
2. Calculation and estimation of machine costs, including planned maintenance, expressed in SEK/h for each machine, as well as the plant in whole.
3. Calculation and estimation of production rate, in terms of product flow, expressed in ton/h.
4. Calculation and estimation of downtime for each machine, as well as the plant in whole.
5. Calculation and estimation of balancing losses for each machine.
6. Calculation of the cost/ton for each product respectively.
7. Validate the results from the newly developed production cost model.

2.2. Collection of information

The main sources of information used in during this project were the following:

- Lectures & Interviews. In order to gather information and to get a wider view of C&S plant operations several interviews and lectures took place with experts within different areas. Also interviews at Sandvik in Svedala were made with the purpose to get a greater insight in the organization and in certain operations.
- Literature studies. Literature studies, mainly books, articles, papers and other academic work, such as other master's theses and doctoral theses, has been the major source for knowledge.
- C&S plant visits. During the project two visits at C&S plants were made. That was a great way to get further insight in the actual work of C&S but also presented a great opportunity to bring home valuable data. Numbers of importance for the future work were derived, for example investment costs, costs for raw material, yearly product output and particle size distribution. Prior to the visits information forms were sent to the plants to get the information needed.
- Testing & Sampling. In addition to the interviews, performed at the C&S plant visits, sampling, and later testing, took place. An important factor was the properties of the raw material used.
- Computer software. Different software was used in order to conduct the work: PlantDesigner, Machine Lifetime Operating Cost and Mathcad. The main use of PlantDesigner was to extract material flows in the process and capacity of each machine. The results from C&S visits were fed into the software to acquire a valid result which is later used in the production cost-model. PlantDesigner can also be used as a guideline for verification of the end result. Machine Lifetime Operating Cost was used to evaluate and estimate the costs of wear for the machines used in the process. Mathcad was used for calculation of the production cost model and Monte-Carlo simulations.

3. ADAPTION OF CURRENT COST MODEL

In order to get the generic model (Ståhl, 2012) to work with the current processes of C&S for mining and construction a lot of parameters in the model had to be changed and adapted. One major concern is the fact that the generic model presents the result in cost per part and mining and construction measures the final products by weight. The proposed production cost model is presented below.

$$\begin{aligned}
k_j = & \frac{1}{PF_j} \left[\left[k_B \cdot PF_j \right]_b + \sum_{i=1}^{i=n_s} \frac{k_{cpi}}{M_0} \left[\frac{t_{mfi} \cdot pf_{ij} \cdot M_0}{(1-D_i)(1-q_{Pi})} \right]_{c1} \right. \\
& + \sum_{i=1}^{i=n_s} \frac{k_{CSi}}{M_0} \left[\frac{t_{mfi} \cdot pf_{ij} \cdot M_0}{(1-D_i)(1-q_{Pi})} \cdot \frac{q_{Si}}{(1-q_{Si})} + T_{sui} + \frac{1-U_{RB}}{U_{RB}} \left(\frac{t_{mfi} \cdot pf_{ij} \cdot M_0}{(1-D_i)(1-q_{Pi})(1-q_{Si})} + T_{sui} \right) \right]_{c2} \\
& \left. + \frac{k_D}{M_0} \left[\frac{t_{mfS} \cdot PF_j \cdot M_0}{(1-D_S)(1-q_{Ps})(1-q_{Ss})} + T_{sus} + \frac{1-U_{RB}}{U_{RB}} \left(\frac{t_{mfS} \cdot PF_j \cdot M_0}{(1-D_S)(1-q_{Ps})(1-q_{Ss})} + T_{sus} \right) \right]_d \right] \quad (1)
\end{aligned}$$

In the following paragraphs this proposed model is described along with relevant changes made.

3.1. Cost per metric ton of product j , k_j

When doing analyses on the production cost for mining and construction it was early found that the generic model would not be sufficient. One reason for this is the fact that there often is a presence of multiple products at a C&S-plant. The generic model is made for a production system with only one product and to make to work for the current application changes were made. The goal was to be able to choose either product at a plant and to

present the cost for this particular one. Two things were altered from the generic model, the most important issue was how to distribute the different costs between the different product fractions. To make the cost distribution fair it was decided to look into the flow for each product fraction in every stage of the process. PF_j is defined as the fraction of one product fraction j at the end of the process. For example, consider two products and that one ton of raw material is run through the process and from this one ton there is 650 kg of product one, that will lead to a PF_1 of 0.65 and hence to a PF_2 of 0.35. This factor can be found in material cost term b and payroll cost term d and distributes these costs in desired way on to the different products. The second issue was how to distribute the machine costs (k_{CP} and k_{CS}) in a good way. The decision was to find the ratio of each product in every machine and through this divide the cost on each product fraction. This is done by monitoring the distribution of particle size through every machine in the process, and thus makes every product account for as much of the machine cost as it is utilizing each machine. These factors are called pf_{ij} and is denoted as the flow of product j in machine i . When doing like the previous paragraphs proposes the cost of a product is presented as a ratio of one metric ton, and in order to get the cost per ton the whole cost must be divided with PF_j which can be found at the very beginning of the proposed model. An important thing to remember is that when having multiple products is the difficulty to compare one product cost with another straight off. It is important to remember that all products are related to each other through specific ratios. For example, if two products are processed one ton of product one also brings a certain amount of product number two which also accounts for a cost per ton and cannot be neglected. It is therefore important to have all the products in mind when performing these calculations to present a valid result.

3.2. Cycle time t_0

Another example where changes were needed to be made is the cost for machines, which is defined as the cycle time t_0 multiplied by the hourly machine cost k_{CP} . A parameter, t_{mf} , that is introduced, represents the time for processing one metric ton of raw material where the material flow m_f is described in metric tons per hour. This resulted in the replacement of the parameter t_0 being replaced by t_{mf} and the result ends up to be a cost per metric ton, which was the original intention.

3.3. Batch size N_0

The batch size is present in all terms in the generic model and must be changed since mining and construction products are measured by weight and not in number of parts. The solution chosen is to switch N_0 for M_0 which is defined as one metric ton of raw material entered in the process.

3.4. Material spill rate q_B

Since C&S in general does not separate material from a main product but rather only downsize entered material into different fractions there is no material spill rate to consider except for a few ppm that disappears as dust. C&S deals with great weights and volumes and most products command a value, either positive or negative, they all need to be accounted for. Due to this fact the choice was to remove the spill rate in the proposed model.

3.5. Reject rate q_0

There are no rejects in mining and construction, a product cannot be destroyed or be required to be scrapped. In some cases there is material, such as sand or gravel of some kinds are considered scraps. But they still command a value, a negative one and are considered a product that is already accounted for. This has led to the removal of the reject rate in the proposed model.

3.6. Balancing losses D

An important parameter in C&S processes is the presence of balancing losses. Balancing loss is defined as the downtime due to a previous station, caused by different cycle times. An example is when a crusher is waiting for material from a slow feed. Crushers are designed to run at maximum capacity when running, it is either down or running at 100 % of capacity. However the aim is to have a grade of utilization for a crusher at around 80 % depending on which step in the process it belongs to, for example the grade of utilization should be high, preferably close to 100 %, at the last crushing stage.

3.7. Multiple stations

The generic model is designed to focus on the steering station, or bottleneck, of the process. This means that all calculations are based on this station and all other stations are adapted to this one. In order to increase the accuracy and quality of the results in this thesis the decision was made to make calculations for each station or machine in the process. This means that both term $c1$ and $c2$ will be changed into the sum for all stages in the

C&S process. By making these changes it will lead to more precise information being available, making the results even more accurate than with the generic model.

3.8. Descriptions of cost model parameters

k_{CP} is denoted as the cost for operating a station or machine during processing. It includes costs only for uptime. It is defined according to the following equation:

$$k_{CP} = \frac{\alpha_f \cdot K_0 \cdot r_a (1 + k_{ren} \cdot N_{ren}) + Y \cdot k_Y + T_{plan} \cdot \left(\frac{k_{UHh}}{h_{UH}} + k_{ph} \right)}{T_{plan}} \quad (2)$$

Where α_f , the annuity factor is calculated with the following equation:

$$\alpha_f = \frac{p \cdot (1 + p)^n}{(1 + p)^n - 1} \quad (3)$$

The original model does not take into account any form of residual value of the equipment. In many cases in high-tech industrial companies' equipment is sold when the economic lifetime has passed. To take into account the residual value it was decided to insert a residual value factor r_a into the k_{CP} and k_{CS} calculations. Through interviews it was decided that it was possible to get around 15 % back of the original investment cost after the expected lifetime of both screens and crushers. With this knowledge the residual value factor r_a was denoted according to the following equation using the present value method:

$$r_a = 1 - \frac{r_{\%}}{(1 + p)^n} \quad (3)$$

Where $r_{\%}$ is the residual value in percent of the original investment, p is the internal rate and n is the expected technical lifetime. Using this factor gives a better connection to reality and a more valid production cost per metric ton. Where p is the internal rate and n is the expected technical lifetime. K_0 is the original investment, including costs for transportation, installation and all other costs associated with getting a new machine operable.

$$\bar{k}_{ren} = \frac{\sum_{i=1}^{i=N_{ren}} \frac{k_{renk_i}}{(1 + p)^{n_{renk}}}}{K_0 \cdot N_{ren}} \quad (4)$$

This is the average cost for a renovation based on all renovations done during a machines lifetime. k_{renk} represent the renovation cost for year k and n_{renk} represent the year of the renovation. It is calculated as a fraction of the original investment and, N_{ren} , an integer (trunc) of the number of renovations done during the machine lifetime. It is calculated according to the following equation:

$$N_{ren} = trunc \left(\frac{n \cdot \frac{T_{plan}}{h_y}}{n_{syren}} \right) \quad (5)$$

Where T_{plan} divided by h_y is the planned production time per year, in hours, divided by the number of hours per shift per year. And n_{syren} is the number of shift-years between renovations. $Y \cdot k_Y$ is the cost for the C&S plant or facility in terms of rent or depreciations.

$$\frac{k_{UHh}}{h_{UH}} + k_{ph} \quad (6)$$

This part of the equation is the maintenance cost per hour divided by the number of hours of operation per hour maintenance. Added to this there are the variable machine time costs, which consists of cost for electrical consumption etc. After adding all the uptime costs for the equipment the total cost is divided by the planned production time per year. k_{CS} , or the machine costs for downtime is denoted according to the following equation:

$$k_{CS} = \frac{\alpha_f \cdot K_0 \cdot r_a (1 + k_{ren} \cdot N_{ren}) + Y \cdot k_Y}{T_{plan}} \quad (7)$$

The cost for downtime consists of the exact same parameters as the cost for uptime except for the last term that is removed. The cost parameter K_D is the costs for all personnel connected with the C&S plant at hand. It includes costs for salary, social security costs and holiday compensation. In order to complete the mapping of the process-flow for a C&S plant, to get correct in-data for simulation, visits and live sampling has been executed.

3.9. Dynamic simulation or simplistic Monte-Carlo Simulation

In order to be able to present results with a strong connection to reality it was early on decided to use simulation on parameters where exact results were difficult, or even possible to obtain. The goal was to present all part costs of the adapted cost model with simulated costs with confidential intervals or with histograms and frequency. As a tool Monte-Carlo simulation was used, which is a simulation method using statistical distribution to decide uncertain variable parameters. Weibull is a suitable probability distribution for applications like lifetime and reliability engineering (Blom *et al.*, 2005).

5. RESULTS AND DISCUSSION

The proposed production cost model was, when finalized, tested at a real C&S site. The model indicated a total mean production cost of 44.2 SEK/ton. Consisting of mean cost for raw material, payroll costs, machine costs during uptime and machine costs during downtime of 15.9, 5.3, 20.5 and 2.5 SEK/ton respectively. All four cost terms along with the total production cost are presented below.

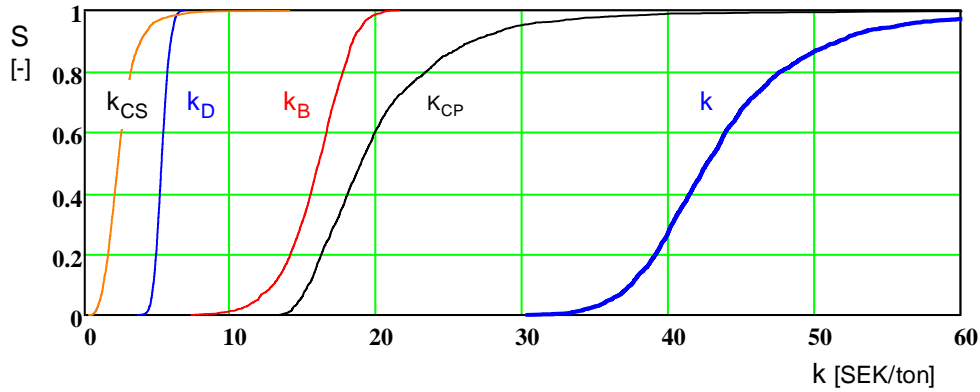


Fig. 1. All cost term distribution functions with the total added cost at the far right.

Since it is difficult to determine exact results and distribute costs to this day in the industry it is difficult to argue around the validity of each figure. But an important thing to enlighten is, when performing the sensitivity analyses using the one-factor-at-time method, that when only changing one factor the analysis does not take into consideration dependencies between factors, which is often the case in the reality (Montgomery, 2009 and Saltelli *et al.*, 2008). Regarding the investment costs it was found that the model's results were almost identical to the plant's own costs when removing the investment costs of all the equipment. This speaks for the validity of the model since the plant's own costs are calculated without investment costs.

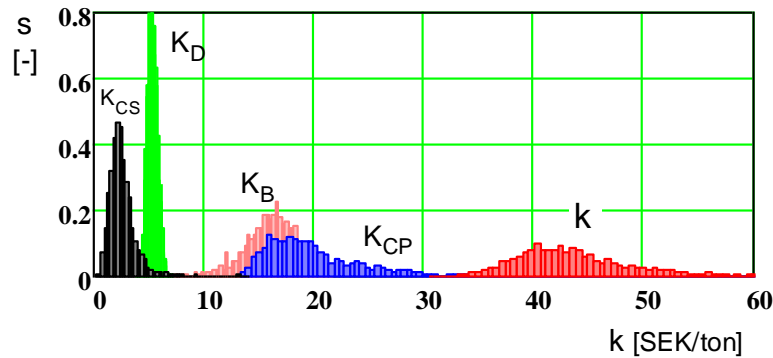


Fig. 2. All cost term frequency functions Weibull distributions with the total added cost at the far right.

For the future there are numerous possibilities and areas of use for this new production cost model. There is a lot of room for improvement and changes in the future.

- **Increase level of user friendliness**

One problem with the new model is the high level of complexity; it takes a lot of knowledge of it to be able to use it in a correct way. For the model to be successful there is a need for a simpler way of use, by now the model is in need of manual adaptation between different sites. The model is currently only created in Mathcad and demands a lot of work. One possibility is to create a script in Excel where all data needed could be entered easily and later imported into the model in Mathcad, which would be a much more efficient way of use.

- **Extended professional sales tool**

If the model was made to be easy to use and present the result in a visually appealing way it would be a great way of presenting costs for customers. For customers in this industry, where production costs are very hard to calculate, it would be a great sales pitch to be able to give them a good indication of probable production costs.

- **Adapt model to other mining and construction areas**

The model could be extended and thereby applicable to some of the other areas in the mining and construction industries. Areas suitable for application are the milling processes and the ore dressing processes. An extension of the model over these areas would create an interesting connection between them and a lot of valuable information would be available.

It can be stated that the proposed adapted production cost model presents a very accurate production cost if used in a correct way. However it has only been tested fully at one C&S site and will require additional testing before presenting it as a valid model.

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