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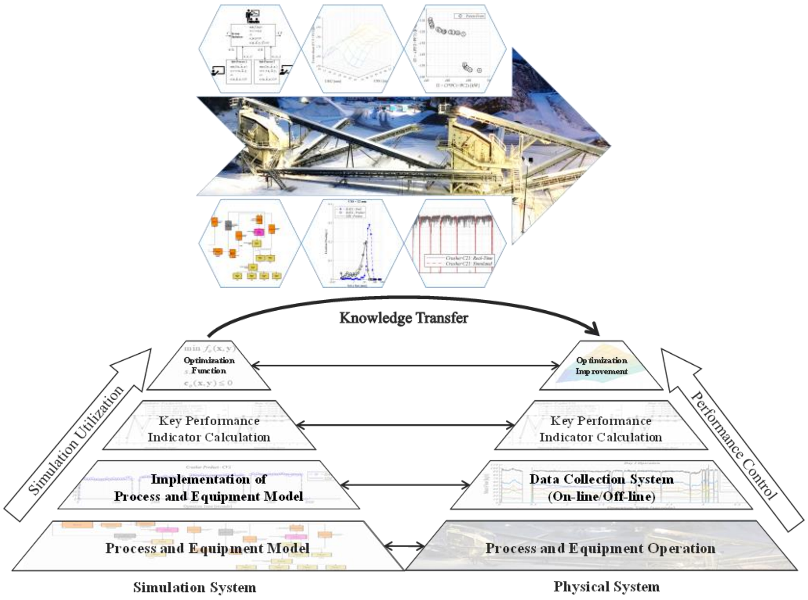
OPTIMERING AV VERKLIGA PROCESSER FÖR BERGMATERIALPRODUKTION

Optimization for rock material production



Kanishk Bhadani, Gauti Asbjörnsson, Erik Hulthén

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Forward

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Summary

The operations of crushing plants are complex and require a broad understanding by the personnel involved, which is developed by training and experience. This creates a need to develop methods and tools which can facilitate and support the operation of the crushing plant to maximize the utilization of the given resources. Process knowledge and understanding are needed to make proactive decisions to enable operations to maintain and elevate performance levels.

The research project aimed to develop and apply optimization capabilities to crushing plant process simulations. The project involved the conduction of multiple experimental and numerical studies performed in collaboration with the industrial partners. During the project, multiple methods in a toolbox are developed, applied, and evaluated within the optimization capabilities of the crushing plant. This toolbox includes methods for optimization functionality, key performance indicators calculation, calibration validation of process simulation, and reliability of production data. Standard optimization problem formulations for each of the applications are demonstrated, which is essential for the replicability of the application. The proposed optimization framework poses a need in the future development of a large-scale integrated digital solution for realizing the potential of production data, simulation, and optimization. In conclusion, optimization capabilities are essential for the modernization of the decision-making process in crushing plant operations.

Innehåll

Introduction

The profitability of the rock material production industry is sensitive to the demand and supply of different aggregates' products. Correct production of rock materials (quantity and quality) to the requirements of the customer is an underlying need to run a crushing plant site in a profitable state. There are large gaps between how a plant is intended to be run in theory compared to how they are operated practically. The optimization of the production in the aggregates industry is driven by the desire to control and drive production towards the requirements of the customer demand and the requirements of the society to minimize waste material production. The rock material industry is a heavy industry in Sweden that produces 90-100 million tonnes of products every year (SGU, 2020). Every improvement, therefore, has a great effect. This project provides the basis for production-oriented and continuous control and thus opportunities for significant financial savings and reduced environmental effects.

Background to Technological Development

The operation and understanding of a crushing plant are complex in nature as there exist dependencies between various equipment and sub-processes. To capture these complex relationships, a process simulation, which is one of the cost-effective tools accepted by the industry, is often used. Steady-state simulation represents an instantaneous mass balancing of the crushing plant circuit, while dynamic simulation can imitate time-dependent phenomena in the crushing plant circuit such as discrete and gradual changes due to material delays, start-up sequence, wear, control, etc (Asbjörnsson, 2015). The process simulation has been successful in helping designers to plan and create virtual crushing circuits but is limited in providing functionality such as optimization of production in daily plant operations. Through appropriate use of the simulation platforms, there are possibilities to create decision-making tools for the daily operation of the production process.

In aggregates production, the aim is often to produce multiple products based on the size specification (e.g., 0/16 mm, 11/16 mm, 5/8 mm, etc.). For a company, it is often desired to maintain sufficient stock levels to be competitive and at the same time, it is desired to not produce non-sellable products. The present technology in aggregates production is limited to eliminating by-products, although there are opportunities to reduce the ratio of non-desired products to desired products. This requires development in optimization methods that can enable such functionality. Production data are captured during the process operation, which is often utilized for process monitoring, production accountability, equipment health and to some extent plant control. There are opportunities to utilize data collected for performing process improvements as well as to understand process optimization.

Purpose

The purpose of the project is to develop, build, and verify optimization methods for rock material production. The question which arises here is how we can enable aggregates production processes to optimize performance based on daily operational needs? The outcome of the project can lead to technological development in using and applying process simulation capabilities for aggregate production at an industrial scale. This can further propel digitalization-related innovation for the aggregate production industry. The application can enable the identification of improvement areas and finding new strategies for operating rock material production. The optimization objective can be steered at increasing the economic and resource sustainability of the industry.

Experimental Studies and Outcome

Controlled experiments are required to develop optimization capabilities in the crushing plant. The following considerations are made for the development work:

- To make decisions using a simulation platform, it is required to maintain the reliability of the process simulation models and it is required to develop efficient methods to achieve this.
- To make decisions using production data, it is required to maintain the accuracy and reliability of the underlying data.
- To perform optimization applications for process operation, it is required to identify the scalability and magnitude of optimization opportunities present in the crushing plant.

The project was carried out in collaboration with three partner companies: NCC Industry AB, Swerock AB and Skanska Industrial Solutions AB. The collaborating companies provided crushing plant sites each to perform experimental studies for the project. A brief description of each study performed on crushing sites is presented in the following section. The details of each study can be found in individual company reports and referenced research articles. Also, a few examples are shown in the Appendix of this report.

Study 1: Investigation of Continuous Mass Flow Measurement in Crushing Plant

Site: NCC Ballast Glimmingen, NCC Industry AB - Tertiary Crushing Process

Background and Purpose: Process optimization and improvement strategies applied in a crushing plant are coupled with the measurement of such improvements, and one of the indicators for improvements is the mass flow at different parts of the circuit. The study was performed to develop a method for calibration of a power-based belt scale which is a cost-effective mass flow estimation technique. For mass flow data, it is also required that the system maintains its accuracy.

Method Development:

- Calibration of accessible power-based belt scale using error minimization optimization problem and physical measurements.
- Calibration of non-accessible power-based belt scale using error minimization optimization problem and mass balance system property of the circuit.

- A novel approach toward tracking deviation in the mass flow measurements using the correlation matrix and mass balance system property of the circuit.

Reference Details: Journal Publication (Bhadani et al., 2021a) and Company Internal Report - NCC

Bhadani, K., Asbjörnsson, G., Hulthén, E., Hofling, K., & Evertsson, M. (2021). *Application of Optimization Method for Calibration and Maintenance of Power-Based Belt Scale*. Minerals, 11(4).

Study 2: Calibration and Validation of Dynamic Process Simulation for Crushing Plant

Site: Skene Kross, Skanska Industrial Solutions AB

Background and Purpose: Dynamic process simulations can capture the change in production performance of aggregate production over time. However, there is a need to develop cost-efficient methodologies to integrate calibrations and validation of models. The purpose of the survey was to map equipment performance, and process performance of the crushing plant in two forms of data: production data for continuous performance as well as belt cut samples for snapshot performance, see Figure 1.

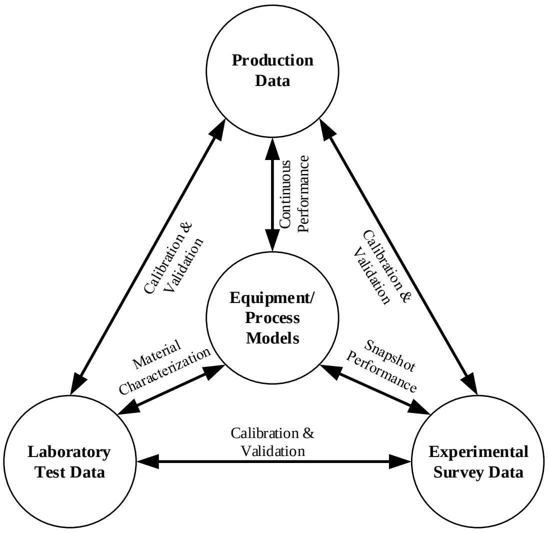

Figure 1. A generalized view of the model and process calibration based on the sources of data.

Integration of calibration methodologies for the dynamic process models to the digital data collection system such as mass flow and power draw can be a powerful and cost-efficient tool. The integration between the dynamic process simulation and online data capturing techniques can eliminate or reduce expensive survey sampling in future. These require the development of suitable optimization methods as well as proof of concept if it can be possible.

Method Development:

- Method for crusher model calibration using error minimization optimization problem in two steps: Capacity Optimization and Product Size Distribution Optimization. A fast mechanistic model based on Evertsson (2000) was used. The use weighting function to generate a good fit of the crusher model was shown together with the application gradient-based algorithm (Quasi-Newton Method) to solve the optimization problem.
- Method for screen model calibration using error minimization optimization problem. Modified Whiten (Napier-Munn et al., 1996) screen model was used.

- Experimental design for the collection of continuous production data and belt cut survey was demonstrated.
- A comparison of the results between the dynamic process simulation and production data was performed, which showed a low error value.
- The interaction effect between the crusher performance and screens performance was demonstrated, and one needs to consider a systems perspective to effectively utilize the process simulation capabilities.

Figure 2. Experimental samples were collected at Skene Kross, Skanska.

Reference Details: Journal Publication (Bhadani et al., 2021b) and Company Internal Report - Skanska

Bhadani, K., Asbjörnsson, G., Schnitzer, B. M., Quist, J., Hansson, C., Hulthén, E., & Evertsson, M. (2021). *Applied Calibration and Validation Method of Dynamic Process Simulation for Crushing Plants*. Minerals, 11(9).

Study 3: Investigation of Crusher Performance with Varying Feed Material

Site: Kållered Bergtäkt, Swerock AB - Tertiary and Quaternary Crushing Process

Background and Purpose: Operational flexibility in an aggregate production process is required to adapt to changes in customer demands. Excessive demand for a particular product fraction can lead to operational alteration wherein re-crushing of the existing larger sized product fraction is necessary. The choice of re-crushing existing product fractions results in feed condition change to the crusher. Controlled experimental survey data with varied feed conditions are needed to calibrate the crusher model.

Method Development:

- An experimental survey to map the performance of the quaternary crusher was performed - Three feed sizes and three crusher closed-side settings each (9 tests).
- An experimental survey to map the performance of the tertiary crusher was performed - one feed size and four crusher closed-side settings (4 tests).
- Analysis of the data made to determine relative product yield, and absolute product yield to demonstrate the potential for optimization.

Figure 3. Experimental samples were collected at Kållered, Swerock.

Reference Details: Company Internal Report - Swerock

Study 4: Investigation of Crushing Plant Performance with Two Crusher Variables

Site: NCC Ballast Glimmingen, NCC Industry AB - Tertiary Crushing Process

Background and Purpose: Applying an optimization solution to the physical crushing site is linked to the number of operational variables present in the crushing and screening equipment. To estimate the potential for optimization improvements, a full-scale industrial experiment was carried out with two crusher variables - CSS and Speed. The collection of both belt-cut data and production data can enable validation of the method demonstrated in study 2. Further, the different data set collected can be used to understand the interrelationship, limitation, and opportunities in the performance improvement of the crushing plant.

Figure 4. Experimental samples were collected at NCC, Glimmingen Site.

Method Development:

- A two factor (CSS and Speed) with a three-level design of experiment (DoE) was conducted (9 tests). Two types of data were collected - continuous production data and belt cut survey. This resulted in continuous time series mass flow data as well as discrete data product size distribution and flakiness index.

- Analysis of the data made to determine relative crusher product yield, absolute crusher product yield, variation in flakiness index to crusher variables, screen performance and quality behaviour to demonstrate the potential for optimization.

Reference Details: Company Internal Report - NCC

Optimization Framework Development

A multi-layered modular framework for performing optimization functions for industrial use is presented in Figure 5. The framework consists of two systems – a physical system and a simulation system – both with four sub-levels interacting parallelly. The interaction between the physical system and simulation system (digital twin) describes different abstraction levels and use in the equipment and process performance mapping. The optimization function is hierarchically built over the digital twin of the crushing plant pertaining to the process operation. The desired optimization of the physical system is achieved by translating, modelling, and simulating the physical process, which is then followed by the optimization routine. The results from the simulation system are transferred to the physical system for implementation. The continuous integration of the data into simulation for performance improvement and optimization is a necessary condition for creating a powerful decision-making tool.

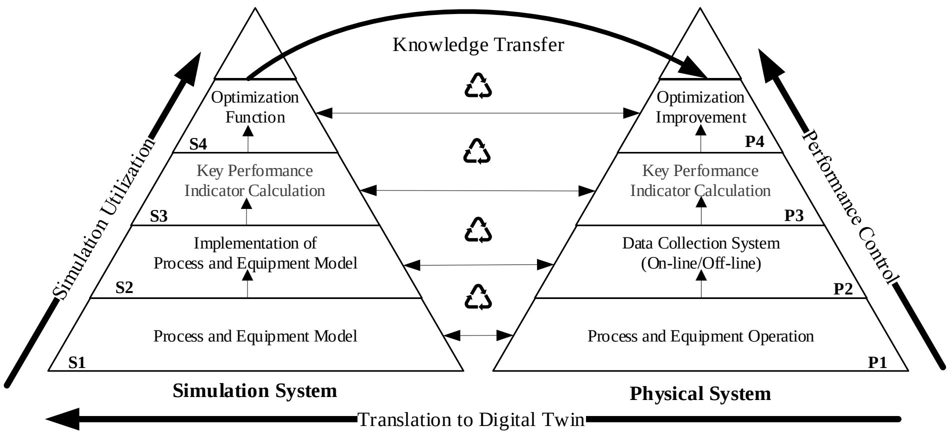

Figure 5. A modular framework for the implementation of optimization capabilities for crushing plants.

Method Development:

- Optimization Function: Multiple optimization methods such as multi-objective optimization (MOO) and multi-disciplinary optimization (MDO) are applied for process optimization.
- Key Performance Indicators: An adaptation of the ISO 22400 standard for the aggregates production process is performed and applied in dynamic simulations of crushing plants.
- Implementation of Process and Equipment Model: A detailed optimization method for calibration and validation of process simulation is presented.
- Data Collection System: Experimental process of capturing continuous and discrete data from crushing plant site demonstrated. Optimization method for creating reliable production data, especially for mass flow data, demonstrated.
- Standard optimization problem formulations for each of the applications are demonstrated, which is essential for the replicability of the application.

Reference Details: PhD Thesis: (Bhadani, 2022)

Bhadani, K., 2022. *Optimization Capabilities for Crushing Plants*, In Department of Industrial and Materials Science. Chalmers University of Technology, Gothenburg, Sweden.

Conclusions and Future Opportunities

Optimization capabilities for crushing plants is a system solution with the two-fold application of:

- Utilizing the simulation platform for identification and exploration of operational settings based on the stakeholder's need to generate knowledge about the process operation
- Assuring the reliability of equipment models, process models and production data to create validated process simulations that can be utilized for process optimization and performance improvements

The project led to the development of multiple methods in a toolbox that can be implemented at different abstraction levels for developing optimization capabilities in crushing plants. The methods developed are based on individual studies performed with different industrial partners. The proposed optimization framework poses a need in the future development of a large-scale integrated digital solution for realizing the potential of production data, simulation, and optimization. In conclusion, optimization capabilities are essential for the modernization of the decision-making process in crushing plant operations.

Future work should include the integration of individual components of the optimization capabilities for crushing plants in an IT solution together with creating an industrial case study for end-to-end implementation of optimization results in an industrial use context. Furthermore, the toolbox can be expanded to include new methods such as equipment and process calibration using continuous production data, and optimization objective function to include economic and sustainability goals. This development process requires close industrial collaboration and can lead to the development of new product features and new ways of operating the crushing plant.

Reference

Asbjörnsson, G., 2015. Crushing Plant Dynamics, In *Department of Product and Production Development*. Chalmers University of Technology, Gothenburg, Sweden.

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Bhadani, K., Asbjörnsson, G., Hulthén, E., Hofling, K., Evertsson, M., Application of Optimization Method for Calibration and Maintenance of Power-Based Belt Scale. Minerals, 2021a, **11(4)**, 412.

Bhadani, K., Asbjörnsson, G., Schnitzer, B., Quist, J., Hansson, C., Hulthén, E., Evertsson, M., Applied Calibration and Validation Method of Dynamic Process Simulation for Crushing Plants. Minerals, 2021b, **11(9)**, 921.

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SGU, 2020. Grus, sand och krossberg 2019: Statistics of the Swedish aggregate production 2019. Sveriges Geologiska Undersökning (Geological Survey of Sweden).

Appendix - Example of Optimization Opportunities

Dynamic Process Simulation and Production Optimization (Refer to Study 2)

Figure 7 presents the comparison of various product streams from the dynamic process simulation to the production data captured from the mass flow system for the four test conditions (T01–T04: left to right) (Bhadani et al., 2021b) for the crushing plant layout (Figure 6).

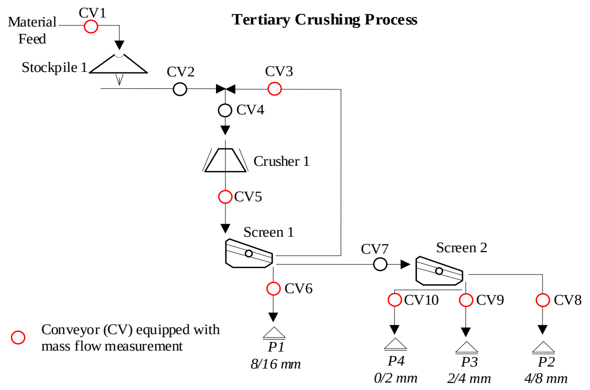

Figure 6 Crushing plant layout for study 2.

It can be observed that the process simulation captures the right trend, phase, and magnitude of the production for different product fractions. The process performance prediction is satisfactory to use such models for process optimization and process planning for aggregate production.

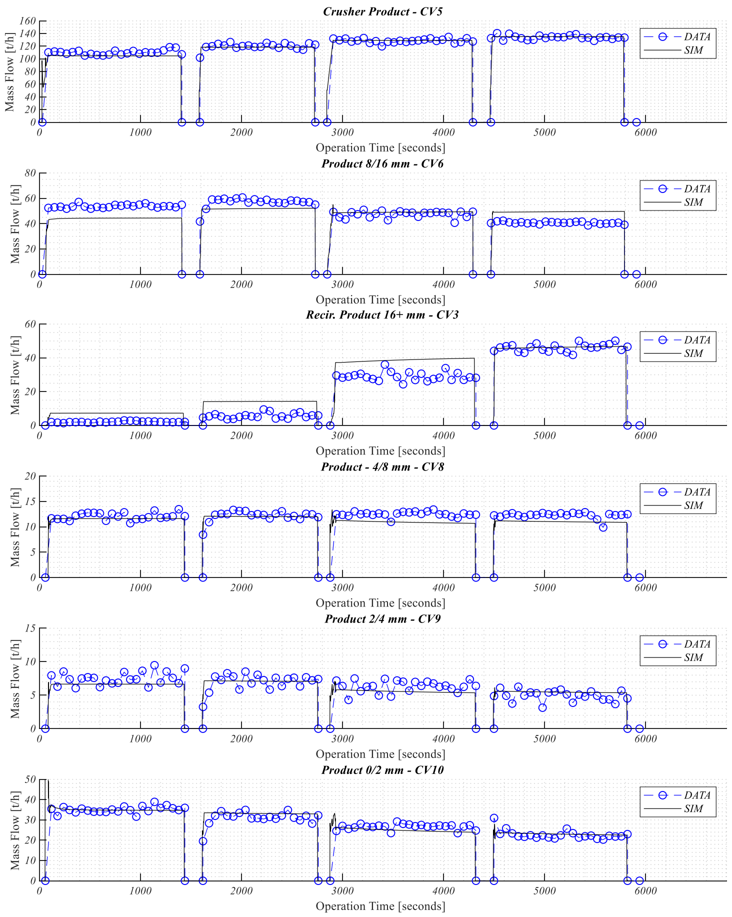

Figure 7. Dynamic simulation process results compared with the online production data for the four test conditions.

<u>Experimental production optimization</u> (Refer to Study 4)

Figures 8 and 9 present the relative and absolute product yield from the crusher for different products for the crushing plant layout shown in Figure 10. The potential for optimization improvements in a full-scale industrial crushing plant can be seen with two control variables CSS and Speed of the crusher. Depending on the stakeholders' needs, the process can be optimized.

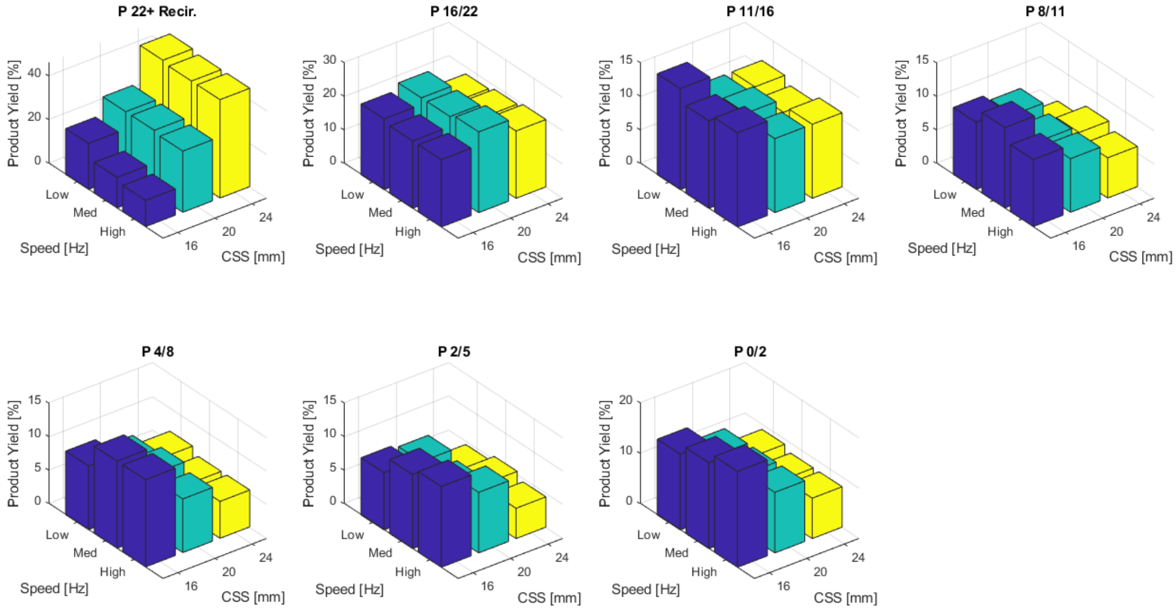

Figure 8 Relative product yield from crusher including recirculating material.

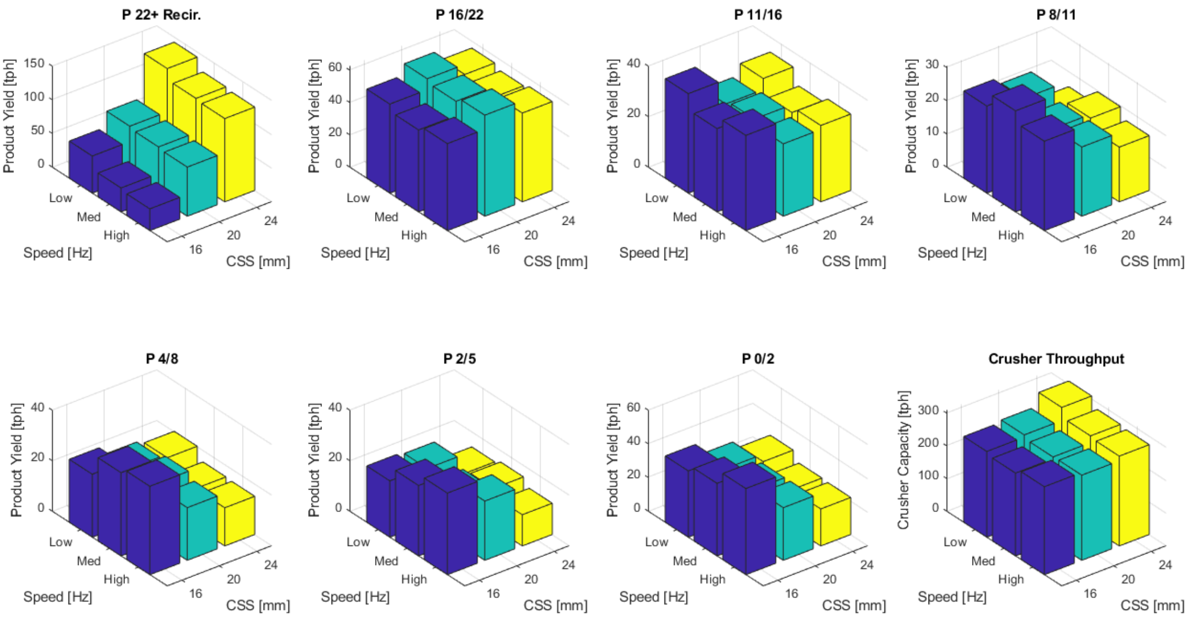

Figure 9 Absolute product yield from crusher including recirculating material.

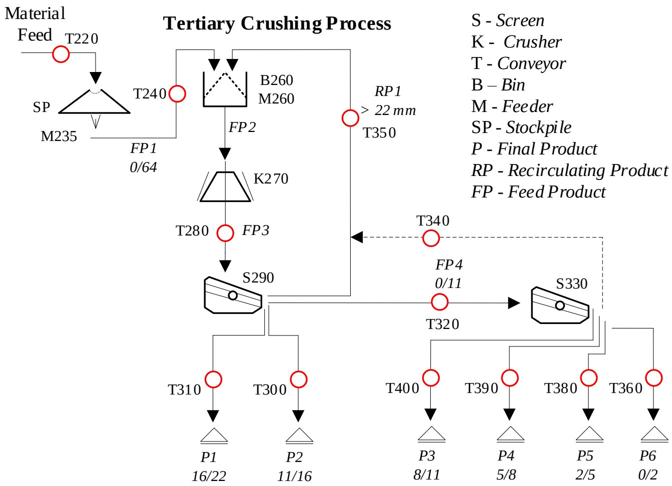

Figure 10 Crushing plant layout for study 2.

<u>Experimental production optimization for varying feed</u> (Refer to Study 3)

Figures 11 and 12 present the relative and absolute product yield from two crushers with different feed material sizes for the crushing plant layout shown in Figure 13. The potential for optimization improvements in a full-scale industrial crushing plant can be seen with feed material control to the crusher. Depending on the stakeholders' needs, the process can be optimized.

Objective: Target is to maximize desired product and minimize undesired product production

Condition: Sufficient stockpile level is present in the plant, reducing waste production and saving resources.

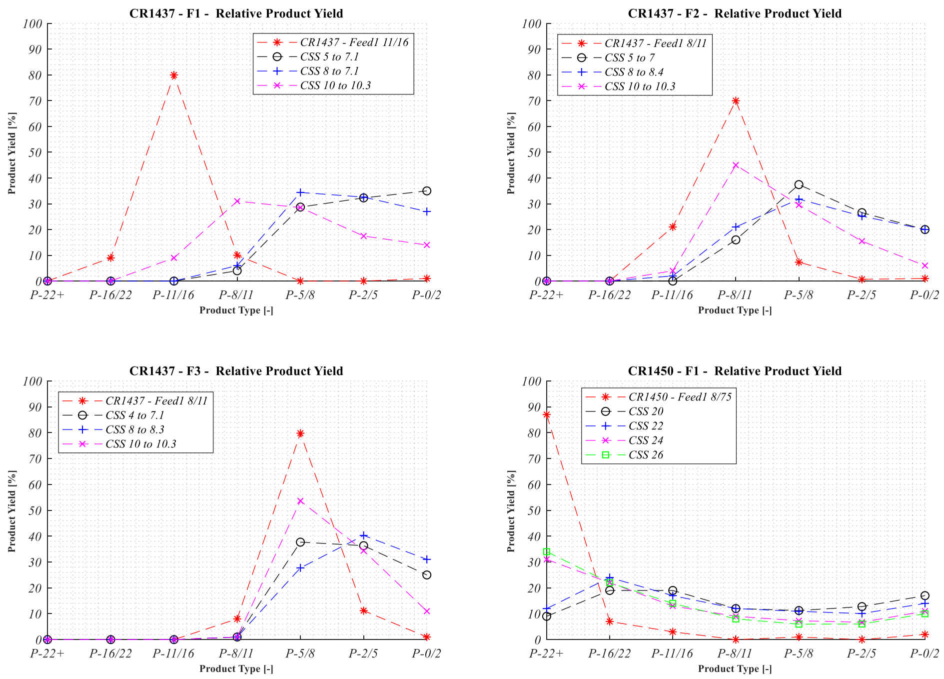

Figure 11 Relative product yield from crusher with varying feed scenarios.

Objective: The target is to maximize desired product stock level.

Condition: Under and overproduction of certain products. Immediate foreseeable sale demand.

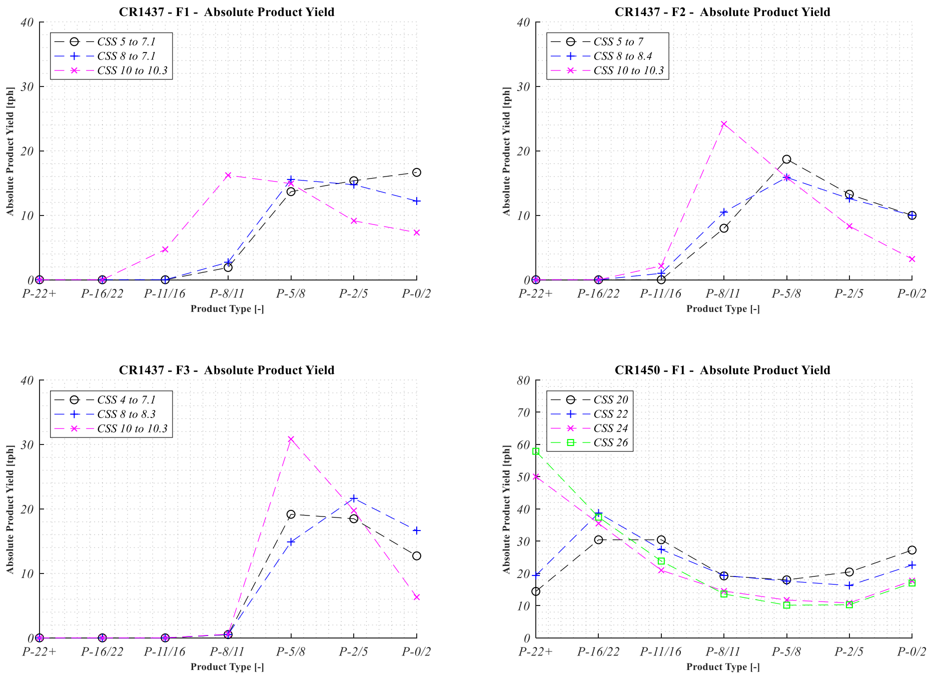

Figure 12 Absolute product yield from crusher with varying feed scenarios.

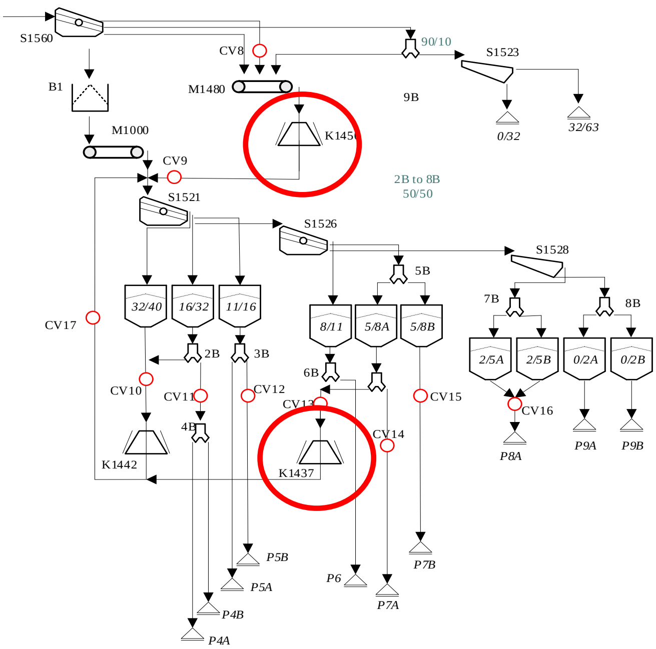

Figure 13 Crushing plant layout for study 3.