Crushing Flowsheet Simulation: Increased Productivity and Improved Flowsheet Design

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A 10-year program to integrate crushing and screening models into daily flowsheet design practice has proven successful. A Circuit Analysis Program (CAP) is used worldwide to design and evaluate new and existing crushing flowsheets. To gain user acceptance of CAP and maximize effectiveness, model development, simulation flexibility, ease of use, and developing international access are key issues. These issues have been resolved effectively resulting in flowsheet simulations to assist in justifying increased capital investment. CAP is presently utilized in Canada, United States, and South Africa with intentions to expand to Europe and Asia.

Introduction

A considerable amount of academic research has been conducted to develop accurate models of unit processes in the mineral industries. However, the industrial application of these models to simulation of plant flowsheets has been limited. In 1983, Nordberg Machinery, a manufacturer of crushing, milling and screening equipment, successfully implemented a computer program for the simulation of crushing and screening flowsheets. This Circuit Analysis Program (CAP) is utilized worldwide for the development and/or analysis of crushing plant flowsheets. CAP has enabled Nordberg to improve both worker productivity and the quality of flowsheet design. With the information generated by CAP, customers can be more confident of a given flowsheet's predicted performance. This information can be utilized by the customer to financially justify capital expenditures based on CAP's simulation predictions. Typical applications include:

1. New Flowsheet design
2. Study and modification of existing flowsheets
3. Plant studies for evaluation of automation potential.

The development of CAP encompassed several years, and its successful implementation was a result of resolving problems related to model development, simulation flexibility, ease of use, and international access. The context of this paper will focus on these areas and conclude with a case study of a recent flowsheet design and plant study.

Model development

The model development is a result of data collected from laboratory tests and field data collected on crushing and screening equipment. A generalized screening model (figure 1) similar to one presented by Karra (1979) has been developed. As shown in figure 1, a screening oversize partition curve is developed from the algorithm:
FIGURE 1. Normalized oversize position curve for screen model

\[ \%C_1 = 100 \left(1 - \exp(-0.693(d_i/d_{50})^{K_1}) \right) \]

where: \( \%C_1 \) is the oversize partition coefficient,
\( d_i \) is the geometric mean particle size
\( d_{50} \) is the mean particle size where 50% passes
\( K_1 \) is a statistically determined constant related to the designed screen dynamics.

Each size gradation is separated via the composition of this partition curve. The screen model allows CAP to account for screen inefficiency which varies depending on the amount of near size material, fineness of separation, and surface characteristics of the material. Screens are sized relative to internationally accepted screen sizing practice.

Field data has been collected to determine the performance of Gyratory, Cone, Gyradisc, Jaw and Impact crushers. CAP's crushing models enable simulation of all these crushing devices. As shown in figure 2, the crushing performance of a given machine is determined by the user-selected liner, crusher setting, throw, and type of crusher. Connected horsepower, speed, and throw are generally assumed constant for a given size and type of machine. Provisions have been made in the program to include any crushing or agglomeration device in the circuit provided the gradation and production characteristics of that device are known.

The crushing and screening models within CAP provide satisfactory estimates of crushing and screening performance. The most confident model predictions are based on actual field performance of existing equipment for a given material. Model development for CAP will continue as additional data is collected.

**Simulation flexibility**

Lack of simulation flexibility is a common problem of many commercially available simulation packages. Customers, particu-
larly those customers producing aggregate products, utilize a wide variety of flowsheet configurations. In addition, two plants producing identical products can be designed with widely varying flowsheets. The speed with which a flowsheet can be simulated enables a user to examine several flowsheet options. The final design is determined by economics, company practice, individual preference, and technical performance. For successful flowsheet simulation of crushing and screening circuits, CAP's simulation flexibility is an absolute requirement.

Simulation flexibility is the principal technical strength of CAP. With this flowsheet simulator users, in a matter of minutes for each simulation, can conduct a performance analysis of changing operating conditions. CAP is used for 99% of all flowsheet analysis by North American users. Typical examples include:

1. The increased production from higher performance crushers.
2. The effect of modifying screen performance on crusher loading.
3. Reduced circulating loads from tighter crusher settings.
4. Finer products from tighter crusher settings.
5. Creating different products by modifying material flows.
6. Identification of flowsheet bottlenecks.
7. Effect of material crushing characteristics on circuit performance.

A crushing/screening flowsheet can be simulated by dividing the flowsheet into simulation stages. Each stage can contain 1-100 identical crushers and 1-100 identical screens. A maximum of eight simulation stages are allowed. Each stage has the ability to simulate splitters for splitting material flows into multiple streams. Material flows can be transferred directly from stage to stage, deposited in one of eight available product bins or nine available surge bins, or recirculated to a previously simulated component. By combining surge and product bins, a total of 17 different final products can be created.

**Ease of use**

The potential users of CAP are application and sales engineers. Many of these users have minimal experience with computers or computer models. Successful development of CAP requires user-friendly input and error prevention procedures. Early efforts to implement these models at Nordberg failed mainly due to difficult execution procedures.

Data processing experts were consulted to develop easier to use input and output

![Diagram of CAP simulation process](image)

**FIGURE 3.** Final structure of CAP for USA users. COBOL programs handle input/output and FORTRAN program models flowsheet.
formats. CAP was transferred from a time-sharing CDC mainframe to Nordberg's Milwaukee IBM mainframe. The Milwaukee mainframe's VMSP system provided full-screen edit capabilities for creating data files. The data processing staff developed COBOL software for data handling and error checking.

With the use of full-screen editing and the development of error checking COBOL software, the final structure (figure 3) of CAP was completed. These enhancements transformed CAP from TTY batch operation to a full-screen interactive program. As a result, user acceptance was achieved.

**International access**

After CAP had been successfully implemented in Milwaukee, a study was conducted regarding international access to CAP. Two locations, Guelph, Canada and Johannesburg, South Africa agreed to test and implement CAP.

A review of problems associated with international access identified key areas of concern, specifically:

1. Program security.
2. Establishing communication links.
3. Economic costs.
4. Ease of use and troubleshooting.

As international access became a priority, maintaining the security of CAP became the key issue. Recent developments in personal computer technology made available the possibility of converting the entire software for execution on a PC. However, maintaining program security would be almost impossible with the current technology. The PC option was quickly rejected.

The final choice for maintaining the maximum program security became establish-
FIGURE 4. International users' simulation/data transfer environment. Personal computer acts as an intelligent terminal for input data development and output editing.

Computer as an intelligent terminal, communications and execution costs were reduced an average of 75%. Subsequent enhancements include: 1) on-line help facility, 2) File handling utility, and 3) Electronic mail system for reporting problems.

Case study: 450 tph aggregate plant
A North American consulting company is responsible for the design and construction of a basalt aggregate plant. Production specifications and requirements forwarded to Nordberg Application Engineers included:

- 375 Metric Tons per hour (MTPH) of 32mm by 0 blend.
- 40 Metric Tons per hour (MTPH) of 17mm by 0 blend.
- 35 Metric Tons per hour (MTPH) of 17mm by 10 mesh blend.

The initial request from the consultant was for quotation of a Jaw/Cone crushing plant to produce the desired products. Earlier manual estimates by competitive manufacturers indicated that the plant production could be met with one 1109 Jaw Crusher and two 1.3 meter cone crushers. To fully determine the equipment required to meet product specifications, CAP was utilized to determine plant performance under two options, specifically:

Option 1. One 1109 VB Jaw Crusher
   Two 1560 Omnicone Cone Crushers
   Base design on 90 to 85% screening efficiency.
   (see flowsheet in figure 5)

Option 2. One 1109 VB Jaw Crusher
   Two 1560 Omnicone Cone Crushers
   One 48 inch (1.2 meter) Nordberg Gyradisc
   Base design on 90 to 85% screening efficiency. (see flowsheet in figure 6)
FIGURE 5. Tertiary crushing circuit with production capability of 425 tph of basalt aggregates.
FIGURE 6. Quartenary crushing circuit with production capability exceeding 450 tph of basalt aggregates
Option 1 was simulated at the request of the consulting contractor. Option 2 was simulated as the Nordberg recommended flowsheet design to guarantee meeting the customer's requirements. The simulated performance comparison of the two options is outlined in Tables I and II. The CAP simulation of the quaternary stage for option 2 is presented in the attached Appendix.

The data in Table I indicates total plant productivity and compares individual crusher performance for options 1 and 2. This data summary clearly indicates that option 2, the quaternary crushing circuit, is required to meet the customer's production requirements. Option 1 could not produce enough fine aggregate to meet product specifications and achieved a maximum capacity of 425 TPH. Option 2, with the additional quaternary crushing stage, met the customers' production requirements.

TABLE I

Production Comparison on Flowsheet Simulation Options. Option 1 is a three-stage crushing circuit with a flowsheet as shown in figure 5. Option 2 is a four-stage crushing circuit with a flowsheet as shown in figure 6.

<table>
<thead>
<tr>
<th>Run of Quarry Feedrate:</th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>425 TPH</td>
<td>450 TPH</td>
</tr>
</tbody>
</table>

Primary Scalper Performance
- Scalper Oversize (635mm x 100mm): 277 TPH 294 TPH
- Scalper Undersize (-200mm x 0mm): 148 TPH 156 TPH

VB 1109 Jaw Crusher Performance
- Closed Side Setting: 155 mm 165 mm
- Total Feedrate: 277 TPH 294 TPH
- % of Full Load Capacity: 99% 98%

1560 Omnicone Cone Crusher Performance (Secondary)
- Closed Side Setting: 30 mm 38 mm
- New Feedrate: 296 TPH 317 TPH
- Total Feedrate: 313 TPH 374 TPH
- % of Full Load Capacity: 88% 98%

1560 Omnicone Cone Crusher Performance (Tertiary)
- Closed Side Setting: 13 mm 13 mm
- New Feedrate: 166 TPH 177 TPH
- Total Feedrate: 238 TPH 220 TPH
- % of Full Load Capacity: 97% 95%

48 INCH GYRADISC Performance (Quaternary)
- Closed Side Setting: 13 mm 13 mm
- New Feedrate: 48 TPH 48 TPH
- Total Feedrate: 93 TPH 93 TPH
- % of Full Load Capacity: 8.4% 70%

Plant Production
- Specified Products
  - 32mm by 0 blend: 387 TPH 378 TPH
  - 17mm by 0 blend: 0 TPH 34 TPH
  - 17mm by 10 mesh blend: 38 TPH 38 TPH
- Total 425 TPH 450 TPH
requirement with extra capacity to produce additional cubical fine aggregates. In this case study, the use of a Circuit Analysis Program had distinct advantages. First, CAP simulations enabled Nordberg to identify the absolute requirement for 1.5 meter cone crushers rather than 1.3 meter cone crushers originally proposed. As a result, the customer could be assured of meeting his plant production objectives. Second, the entire quotation process including examination of several flowsheet options was completed in less than eight hours. A similar analysis without a Circuit Analysis Program would have required several days of work with a lower confidence level in final plant performance.

### TABLE II

Screening Performance Comparison of Flowsheet Simulation Options. Option 1 is a three-stage crushing circuit with a flowsheet as shown in figure 5. Option 2 is a four-stage crushing circuit with a flowsheet as shown in figure 6.

<table>
<thead>
<tr>
<th>Run of Quarry Feedrate</th>
<th>Option 1</th>
<th>Option 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>425 TPH</td>
<td>450 TPH</td>
</tr>
</tbody>
</table>

**Primary Scalper Performance:**
- Scalper Oversize (635mm x 100mm): 277 TPH
- Scalper Undersize (-200mm x 0mm): 148 TPH

**Secondary Screening Performance:**
- Deck One
  - Mesh Opening: 100 mm
  - Screening Efficiency: 95 %
  - Area Required: 5.7 m²
- Deck Two
  - Mesh Opening: 63 mm
  - Screening Efficiency: 92 %
  - Area Required: 6.9 m²
- Deck Three
  - Mesh Opening: 32 mm
  - Screening Efficiency: 89 %
  - Area Required: 11.8 m²

**Tertiary Screening Performance:**
- Deck One
  - Mesh Opening: 17 mm
  - Screening Efficiency: 84 %
  - Area Required: 10.8 m²
- Deck Two
  - Mesh Opening: 9.5 mm
  - Screening Efficiency: 83 %
  - Area Required: 6.5 m²
- Deck Three 88 %
  - Mesh Opening: 4.7 mm
  - Screening Efficiency: 88 %
  - Area Required: 6.5 m²

**Quaternary Screening Performance:**
- Deck One
  - Mesh Opening: 6 mm
  - Screening Efficiency: 94 %
  - Area Required: 4.1 m²
- Deck Two
  - Mesh Opening: 3.3 mm
  - Screening Efficiency: 91 %
  - Area Required: 4.5 m²
Conclusions

The successful implementation of computer models in the industrial environment was achieved through addressing user needs. The program's simulation flexibility coupled with its ease of use has helped CAP gain a wide acceptance. As a result, this flowsheet simulation technology is being utilized on a daily basis for better flowsheet design.

CAP's worldwide implementation was accomplished while meeting security and cost-effectiveness considerations. The key roles of international telecommunications networks and personal computers acting as intelligent terminals enabled preservation of key features and allowed additional enhancements.

CAP is presently being utilized in the United States, Canada and South Africa. Applications include plant studies, flowsheet design, and process control evaluation. A future objective is to extend CAP's use to Brazil, Europe and Australia.

Note CAP (Circuit Analysis Program) is protected by United States federal copyright law. Reproduction and/or use of CAP without the express written permission of Rexnord Inc. is prohibited.

Reference


Appendix: ACAP simulation output of quaternary crushing circuit

DATE - 06/25/87 TIME - 09:06 P A G E 10

STAGE #4 CRUSHING STAGE CONTAINS ( 1) 48 INCH GYRADISC CRUSHER

INDIVIDUAL CRUSHER CAPACITY INDICES
SETUP CRUSHER CRUSHER
SETTING = 1.30 CM. NEW FEED = 48 TPH CAPACITY INDEX= 70%
LINER TYPE=FINE TOTAL FEED= 93 TPH
CIRCUITRY=CLOSED MAX. FEED = 132

PRODUCT MATERIAL ANALYSIS PASSING (CM.) (PERCT)

1.30 100.0
.95 89.0
.70 74.5
.60 68.0
.47 59.0
6M 46.1
10M 36.2
14M 28.0

PRIMARY DESTN: STAGE #4 (S) AMOUNT: 93 (TPH)

P80 = .84 CENTIMETERS.
SCREEN SIZING AND PERFORMANCE ANALYSIS --- STAGE #4
****************************************************************

THEORETICAL AREA REQUIRED.

Below is a table giving the screen sizing factors used to determine the theoretical area of this screen.

Definition of terms:
"OPENING" - EFFECTIVE OPENING OF SCREEN MESH.
"A" - STPH PASSING A SQ. FT. OF SCREEN SURFACE.
"B" - PERCENT OF OVERSIZE IN FEED TO DECK FACTOR.
"C" - PERCENT HALF SIZE IN FEED TO DECK FACTOR.
"D" - DECK LOCATION FACTOR.
"E" - WET SCREENING FACTOR.
"F" - MATERIAL WEIGHT FACTOR.
"G" - SCREEN SURFACE OPEN AREA FACTOR.
"H" - SHAPE OF SURFACE OPENING FACTOR.
"I" - SCREEN SLOPE FACTOR.
"TUST" - THEORETICAL UNDERSIZE TONNAGE.
"AREA" - THEORETICAL AREA REQUIRED.

<table>
<thead>
<tr>
<th>DECK</th>
<th>OPENING CM.</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>TUST MTPH</th>
<th>AREA SQ. M.</th>
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<td>1.22</td>
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<td>1.00</td>
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<td>1.00</td>
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<td>1.00</td>
<td>1.00</td>
<td>42.7</td>
<td>4.5</td>
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A 1.2 X 3.7 METER 2-DECK SCREEN SELECTED FOR THE APPLICATION

<table>
<thead>
<tr>
<th>DECK#</th>
<th>FEED</th>
<th>OVERSZ</th>
<th>UNDRSZ</th>
<th>EFFICY(%)</th>
<th>DBF</th>
<th>DBD</th>
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<tr>
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<tr>
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<td>58</td>
<td>19</td>
<td>39</td>
<td>91</td>
<td>1.6</td>
<td>.5</td>
<td>1.3</td>
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</table>
DATE - 06/25/87 TIME - 09:06

STAGE #4 SCREENING STAGE CONTAINS 1 SCREEN(S) WITH 2 DECK(S).

NEW FEED 48 TOTAL FEED 93

<table>
<thead>
<tr>
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<th>DECK #1</th>
<th>DECK #2</th>
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<td>OVERSIZE</td>
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<td>TONNAGE (TPH)</td>
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<td>PROBABILITY (%)</td>
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<tr>
<td>EFFICIENCY (%)</td>
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FEED ANALYSIS

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<td>28M</td>
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... .SPLIT SCREEN ANALYSIS.......

<table>
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<th>DECK #1</th>
<th>DECK #2</th>
<th>DECK #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVERSZE</td>
<td>OVERSZE</td>
<td>UNDRSZE</td>
</tr>
</tbody>
</table>

PRIMARY DESTN: STAGE #4 (C) STAGE #4 (C) STAGE #4 (C) STOCK BIN(3)
AMOUNT: 35 (TPH) 10 (TPH) 12 (TPH)

SPLIT 1 DESTN: STOCK BIN(3) STOCK BIN(1)
AMOUNT: 10 (TPH) 27 (TPH)

178 METALLURGY: MODELLING