

Development of a computer application for comminution circuit design

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Abstract: Comminution is the most energy-intensive stage of mineral processing and plays a decisive role in plant performance, equipment selection, and operating costs. Consequently, the preliminary design of crushing circuits requires reliable engineering calculations and systematic evaluation of ore characteristics and design criteria. This paper presents the modernization and verification of the C&G Circuit Designer, a computer-aided engineering application developed to generate preliminary crushing circuits based on established comminution design principles. The application integrates particle size distribution analysis, distribution coefficient estimation, equipment selection, reduction ratio evaluation, and stage-wise mass balance calculations within a unified engineering framework, using the Gaudin-Schuhmann particle size distribution model. Verification against an independently prepared reference design showed close agreement in the predicted distribution coefficient, generated crushing circuit, and stage-wise mass balance, confirming the correct implementation of the stated equations; broader validation against industrial plant data or established commercial simulators is identified as necessary future work. Unlike conventional comminution software, which generally requires engineers to define a process flowsheet before analysis, the developed application generates preliminary crushing circuits directly from ore properties and engineering design criteria, providing a consistent basis for subsequent engineering evaluation and detailed plant design. The modular software architecture supports future expansion through additional equipment databases, closed-circuit finishing stages, and optimization modules while preserving the established design methodology.

Keywords: comminution, crushing circuit design, computer-aided engineering, mineral processing application development

1. Introduction

Comminution, comprising crushing and grinding operations, forms the foundation of mineral processing by liberating valuable minerals from surrounding gangue before downstream separation processes. Beyond its essential role in mineral liberation, comminution is the most energy-intensive stage of mineral processing, typically accounting for approximately 40–50% of total energy consumption in concentrators (Wills & Finch, 2016), while also representing a substantial share of both capital investment and operating expenditure. As declining ore grades and increasingly complex mineral deposits demand finer particle liberation and higher processing capacities, improving comminution circuit efficiency has become an important objective.

Designing crushing circuits requires coordinated evaluation of numerous interdependent parameters, including ore properties, feed size distribution, target product size, reduction ratios, equipment characteristics, production capacity, and downstream process requirements. Because these decisions are strongly interdependent, circuit development is inherently iterative and has traditionally relied on laboratory characterization, manufacturers' catalogues, and professional engineering judgement (King, 2001; Napier-Munn et al., 1996; Mular et al., 2002; Wills & Finch, 2016).

Advances in computing technologies have substantially changed engineering practice in mineral processing, making computer-aided software an integral component of comminution circuit design and evaluation. Commercial software packages such as JKSImMet, Bruno, PlantDesigner, and USIM PAC

incorporate well-established mathematical models and equipment databases supporting process simulation, equipment selection, and performance analysis across a wide range of comminution applications (Morrison and Richardson, 2002; Brochot et al., 2002; Kaja, 2002; Hedvall and Nordin, 2002; Herbst et al., 2002; Mular et al., 2002). By replacing repetitive manual calculations with computational analysis, these tools have significantly improved the efficiency, consistency, and reliability of comminution circuit design and evaluation.

JKSimMet uses population balance modeling to simulate and optimize crushing, grinding, and classification circuits. The software incorporates ore-specific breakage parameters obtained from laboratory testing and has been widely applied in circuit optimization, equipment evaluation, and plant performance improvement (Morrison & Richardson, 2002).

Bruno, developed primarily for crushing and screening plant design, integrates equipment selection, production estimation, equipment sizing, and process simulation within a graphical engineering environment. Its user-friendly interface enables engineers to compare alternative equipment configurations and estimate plant production capacities during preliminary design studies (Kaja, 2002).

Similarly, PlantDesigner provides an integrated simulation environment for aggregate and quarry operations by combining process modelling with commercial equipment databases. The software supports evaluating production scenarios and equipment utilization while allowing engineers to explore alternative plant layouts through graphical process modelling (Hedvall & Nordin, 2002).

USIM PAC offers one of the broadest modelling environments by integrating comminution, classification, flotation, gravity concentration, and hydrometallurgical processes within a modular software architecture. Owing to its flexibility and extensive model library, USIM PAC has been widely employed in industrial feasibility studies as well as academic research (Brochot et al., 2002).

More recently, physics-based numerical methods such as the Discrete Element Method (DEM) and Computational Fluid Dynamics (CFD) have significantly complemented these empirical simulators by modelling particle-scale breakage and equipment behaviour directly (Herbst & Nordell, 2002).

Despite this diversity, these platforms share a common characteristic: they are built to analyse, calibrate, and optimize a process flowsheet that the engineer has already defined, rather than to generate a flowsheet from first principles. Table 1 summarizes this distinction across the main commercial platforms and the application presented here.

Table 1. Comparative evaluation of representative comminution circuit design software

Functionality	JKSimMet	Bruno	PlantDesigner	USIM PAC	C&G Circuit Designer
Process simulation	✓	✓	✓	✓	✓
Mass balance calculation	✓	✓	✓	✓	✓
Particle size distribution prediction	✓	✓	✓	✓	✓
Equipment model library	✓	✓	✓	✓	✓
Equipment database	-	✓	✓	✓	✓
Equipment selection support	✓	✓	✓	✓	✓
User-defined process configuration	✓	✓	✓	✓	✓
Automatic determination of crushing stages	—	—	—	—	✓
Automatic preliminary crushing circuit synthesis	—	—	—	—	✓
Automatic flowsheet generation	—	—	—	—	✓

The aim of this study is to address the lack of a computer-aided methodology capable of generating a crushing circuit directly from ore properties and design criteria, rather than analysing a flowsheet already defined by the engineer. This paper presents the C&G Circuit Designer, a computer-aided engineering application that generates crushing circuits from fundamental design parameters using

established comminution design principles (King, 2001; Wills & Finch, 2016), and reports its modernization from a legacy desktop implementation to a maintainable, extensible architecture.

2. Methodology

2.1. C&G circuit designer framework

The design methodology implemented in the C&G Circuit Designer integrates established comminution engineering principles with computer-based decision algorithms. The application accepts ore characteristics and principal design inputs, including feed size, target product size, and capacity, as the primary design inputs. Based on these inputs, the software determines and generates the corresponding crushing circuit configuration. Once the circuit has been generated, the application performs engineering calculations, including mass balance analysis and particle size distribution prediction, to evaluate the resulting design. Fig. 1 illustrates the overall sequence of the C&G Crushing Circuit Designer application.

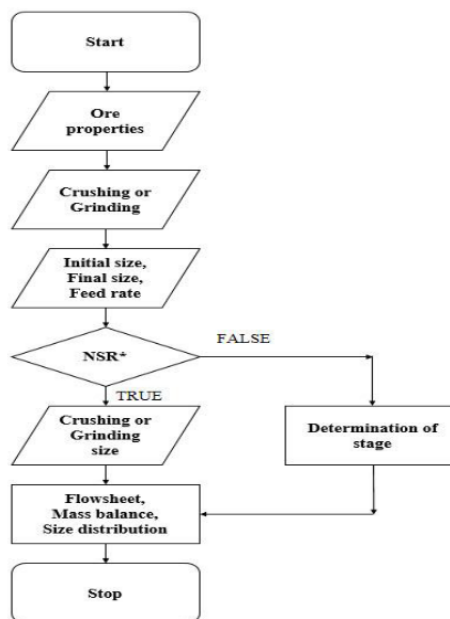


Fig. 1. General algorithm of the C&G Circuit Designer for crushing circuit design (Modified from Recepov, 2019)
NSR*: Number of stages required

Fig. 1 summarises the C&G Circuit Designer's sequence of operations. The process begins by defining the principal design parameters, including ore properties, feed size, target product size, and feed rate. The application then evaluates whether the number of crushing stages has been specified by the user. If this information is available, the crushing circuit is established directly; otherwise, the required number of stages is determined automatically before the circuit flowsheet is created. The generated circuit is subsequently evaluated through mass balance calculations and particle size distribution prediction.

The C&G Circuit Designer operates in two complementary modes. In simulation mode, an existing crushing circuit is defined by the user, and the application performs mass balance calculations together with particle size distribution prediction. In design mode, the circuit layout or the number of crushing stages is unavailable; the application determines the appropriate number of stages, constructs the corresponding crushing circuit, and then performs the same engineering calculations. This dual-mode structure enables both the preliminary design of crushing circuits and the evaluation of existing circuit layouts within a single computational environment.

Moisture effects are neglected, while engineering parameters such as clay content and ore distribution coefficient are constrained within practical operating ranges to maintain numerical stability throughout the calculations. These assumptions simplify the design procedure while remaining consistent with preliminary engineering practice.

The C&G Circuit Designer software architecture comprises five integrated functional modules, as shown in Fig. 2. These modules collectively support engineering data management, automated circuit design, and auxiliary computational functions. Their integration enables the exchange of engineering data and calculation results throughout the design procedure.

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***** C&G Circuit Designer *****

C&G Circuit Designer is a process design and simulation program for
crushing circuit and wet grinding circuit in a mineral processing plant.

The program is created based on literature and works accordingly.

In this program, maximum stage of crushing circuit is 3.
Also, maximum stage of grinding circuit is 2.

The stage of comminution process with proper reduction ratios and distribution coefficient of ore
in log-log graph can be determined if they are unknown.

In NOTIFICATIONS option, some notifications are collected to inform a user.

In PARAMETERS option, there are initial values for each definition used to design and
simulate the circuit in an optimum way. They can be changed by user.

In 4.option, user can determine the distribution coefficient of a specific sample
from the results of sieve analysis.

*****

Start : [1]
Notifications : [2]
Parameters : [3]
Determination of distribution coefficient : [4]
The last saved comminution process : [5]

Enter your choice : _

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Fig. 2. Main interface of the original desktop implementation of C&G Circuit Designer (adapted from Rejepov, 2019)

2.2. Mathematical models and circuit configurations

The mathematical basis of the C&G Circuit Designer is based on a set of mathematical models representing the principal operations of crushing and screening processes. Together, these models provide the analytical framework for circuit configuration, equipment selection, mass balance calculations, and particle size distribution prediction. The following sections describe the mathematical models, crushing circuit configurations, and engineering design parameters used in the C&G Circuit Designer.

2.2.1. Crushing circuit configurations

Crushing circuits can be configured using different combinations of crushers and screening units depending on the required product size, circulating load, and feed rate. This study uses three basic crushing circuit configurations (Fig. 3): (A) open-circuit crushing, (B) closed-circuit crushing with forward classification, and (C) closed-circuit crushing with reverse classification. (Wills & Finch, 2016; Napier-Munn et al., 1996; Rejepov, 2019).

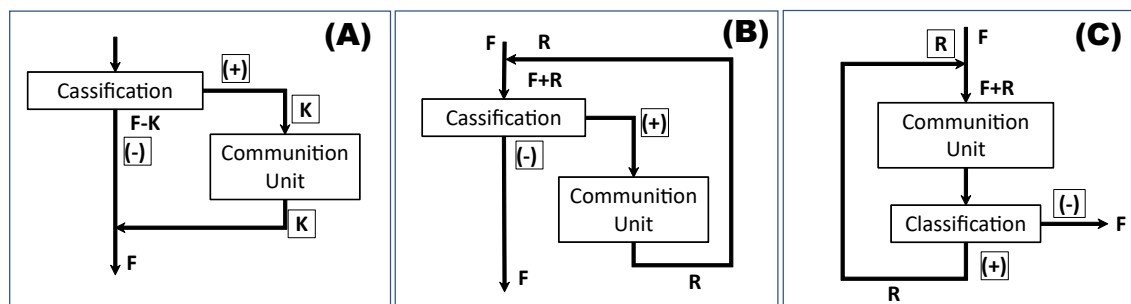


Fig. 3. Three basic crushing circuit configurations used in mineral processing (adapted from Rejepov, 2019, F: Feed rate, K: Feed rate to comminution unit, R: Recirculating load)

The material flow associated with each crushing circuit configuration shown in Figure 3 is expressed by the mathematical equations presented in the following sections.

In the open-circuit configuration in Fig. 3(A), material passes through the comminution unit only once without recirculation. The feed entering the comminution unit is calculated using Eq. (1):

$$K = F(1 - ec) \quad (1)$$

where K is the feed rate to the comminution unit (Mg/h), F is the fresh feed rate (Mg/h), e is the classification efficiency, and c is the cumulative passing fraction at the classification size.

Eq. (1) calculates the feed entering the comminution unit by accounting for the classification efficiency and the material passing the classification size. The calculated feed is then used in the subsequent calculations.

In the closed-circuit configuration with forward classification Fig. 3(B), only oversized particles are directed to the comminution unit. The feed entering the comminution unit, including the circulating load, is calculated using Eq. (2):

$$R = F((1 - c)) / ((1 - (b/e))) \quad (2)$$

where R is the feed to the comminution unit or recirculating load (Mg/h), F is the fresh feed rate (Mg/h), e is the classification efficiency, c is the cumulative passing fraction at the classification size, and b is the bypass fraction of uncrushed or unground material.

Eq. (2) calculates the recirculating load for the forward-classification circuit by considering both the classification efficiency and bypass fraction of uncrushed material.

In the reverse-classification configuration in Fig. 3(C), material is classified after comminution. Crushed particles leave the circuit as the final product, while oversized particles are returned to the comminution unit. The feed entering the comminution unit is calculated using Eq. (3):

$$R = F((1/ec) - 1) \quad (3)$$

where R is the feed to the comminution unit or recirculating load (Mg/h), F is the fresh feed rate (Mg/h), e is the classification efficiency, and c is the cumulative passing fraction at the classification.

Eq. (3) calculates the recirculating load for the reverse-classification circuit, which is subsequently used in the circuit mass balance calculations.

The distribution coefficient is determined from sieve analysis data using least-squares linear regression. In some cases, the initial coarse size fractions do not follow the linear trend of the remaining data. Including all size fractions in the regression may therefore increase the difference from the actual distribution coefficient. The regression line is recalculated after excluding the coarse size fractions. The remaining data therefore satisfy the linearity required for least-squares fitting. The number of excluded size fractions (k) is always a positive integer and is limited to a maximum of ten. The modified regression model is given by Eq. (4), whereas the relationship between n and k is expressed by Eq. (5).

$$m = \frac{(n - k) \sum_{i=k}^n (x_i y_i) - \sum_{i=k}^n (x_i) \sum_{i=k}^n (y_i)}{(n - k) \sum_{i=k}^n (x_i)^2 - \sum_{i=k}^n (y_i)^2} \quad (4)$$

$$n = 3k \quad (5)$$

The modified regression model is evaluated using the correlation coefficient and sample variance. These statistical measures describe the regression model fit and the accuracy of the estimated distribution coefficient. Their mathematical formulations are presented in Eqs. (6)–(13). Higher correlation coefficients indicate better agreement between the regression model and the experimental sieve analysis data.

The quality of the modified regression model is subsequently evaluated using statistical measures. The correlation coefficient and sample variance are calculated to assess the goodness-of-fit of the regression model and the reliability of the estimated distribution coefficient. The corresponding mathematical formulations are presented in Eqs. (6)–(13). In general, higher values of the correlation coefficient indicate better agreement between the regression model and the experimental sieve analysis data.

$$\bar{x} = \frac{\sum_{i=k}^n (x_i)}{v} \quad (6)$$

$$\bar{y} = \frac{\sum_{i=k}^n (y_i)}{v} \quad (7)$$

$$a_0 = \bar{y} - mx_i \quad (8)$$

$$f(x_i) = a_0 + mx_i \quad (9)$$

$$S_r = \sum_{i=k}^n (\bar{y}_i - f(x_i))^2 \quad (10)$$

$$S_t = \sum_{i=k}^n (y_i - \bar{y})^2 \quad (11)$$

$$r = \sqrt{\frac{S_t - S_r}{S_t}} \quad (12)$$

$$S_v = \frac{S_t}{n-1} \quad (13)$$

where, $\bar{x}$, $\bar{y}$ are the arithmetic means of the values; a_0 is the intercept of the regression line; $f(x_i)$ is the predicted value of the regression function; S_r is the sum of squared residuals; S_t is the total sum of squares; r is the correlation coefficient; and S_v is the sample variance.

The equations presented in this section are used by the C&G Circuit Designer to perform mass balance calculations, estimate particle size distributions, and determine the distribution coefficient.

2.3. Application design parameters

The C&G Circuit Designer includes a parameter module containing ore properties, circuit variables, and equipment operating conditions. Initial parameter values were obtained from the literature and may be modified to represent different ore characteristics or project requirements (Rejepov, 2019). Engineering rules for circuit configuration and equipment selection are incorporated into the application. The design parameters used in the C&G Circuit Designer are shown in Fig. 4.

***** For Crushing Circuit *****	
[3 - 6] Requirements of the open circuit without screen for more than one stage	
[3] Minimum requirement of particle size in feed at first stage	: 700 mm
[4] Maximum requirement of cumulative passing of final crushing size at first stage	: 20.00 %
[5] Maximum requirement of cumulative passing of final crushing size at second stage	: 20.00 %
[6] Maximum requirement of the feed rate at first and second stage	: 150.00 t/h
[7] Minimum requirement of percent bypass of uncrushed particles in crusher product for closed circuit	: 10 %
[8] Maximum requirement of the feed rate for one stage crushing	: 10.00 t/h
[9] Limit for maximum size of run of mine ore	: 2000 mm
[10] Limit for maximum feed rate	: 1000 t/h
[11 - 14] % bypass of uncrushed particles for each crusher product	
[11] Cone Crusher product	: 15.00 %
[12] Jaw Crusher product	: 25.00 %
[13] Impact Crusher product	: 40.00 %
[14] Roll Crusher product	: 3.00 %
[15 - 17] Screen efficiency for each stage	
[15] First stage	: 95.00 %
[16] Second stage	: 90.00 %
[17] Third stage	: 85.00 %
[18] Characteristics for distribution coefficient of crusher feed and product at each stage	: Constant

Fig. 4. Crushing circuit design parameters in the C&G Circuit Designer (adapted from Rejepov, 2019)

Fig. 4 shows the parameters available to the user before designing the crushing circuit. These parameters include ore properties, circuit operating limits, crusher product bypass values, stage-specific screen efficiencies, and distribution coefficient settings. Any of these values can be modified according to the design requirements.

The selected parameters are processed, along with the calculation procedures described in the previous section, during crushing circuit design. Circuit configurations that do not satisfy the predefined engineering rules or operating limits are rejected, while acceptable configurations are used to produce the crushing circuit flowsheet.

Crusher and screen selection is carried out simultaneously according to the required reduction ratio and the selected circuit configuration. Screen aperture and screening efficiency are obtained from the classification procedure described in the previous section. Clay content is one of the criteria considered during crusher selection. Depending on the specified clay content and the predefined selection rules, different crusher types may be selected. For example, Jaw and cone crushers are assigned to ores with low clay contents, whereas impact and roll crushers are preferred for ores with higher clay contents.

2.4. Modernization of the C&G circuit designer application

The original version of the C&G Circuit Designer was developed in the C programming language. It incorporated the calculation procedures and engineering logic required for crushing circuit design. However, the graphical interface and visualization options limited the software's practical use and made further development difficult. The application has been modernized to a web-based architecture while preserving the validated calculation procedures for particle size analysis, distribution coefficient estimation, equipment selection, and automatic crushing circuit generation; the changes are limited to the application architecture and interface.

The original desktop application identifies crusher types such as jaw, cone, impact, gyratory, and roll crushers. The web-based version stores crusher and screen catalogue information for individual equipment in a database. Equipment information, including manufacturer, model, power, capacity, operating speed, and size reduction ratio, can be added or updated without modifying the engineering calculation routines. (Akbas, 2021; Tuncok, 2023).

3. Results and discussion

3.1. Verification of distribution coefficient estimation

The distribution coefficient calculated by the C&G Circuit Designer was validated against an independent calculation performed in Microsoft Excel using the sieve analysis data of the reference design case described by Koyuncu (2017). Both calculations were carried out using identical input data and the same regression procedure described in Section 3.2. Fig. 5 presents the regression equation obtained in Microsoft Excel.

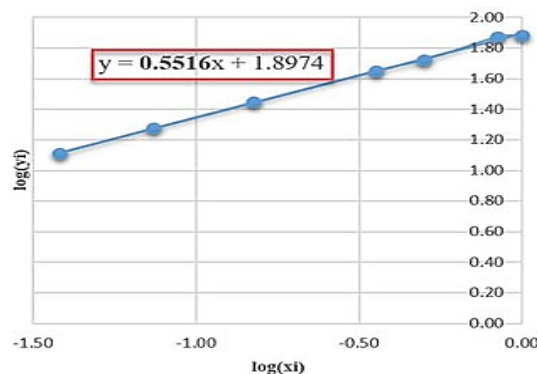


Fig. 5. Determination of the distribution coefficient using linear regression in Microsoft Excel (adapted from Rejepov, 2019)

As shown in Fig. 5, after excluding the coarsest size fractions, the log-log-transformed sieve data follow an approximately linear trend, and Microsoft Excel's regression gives $y = 0.5516x + 1.8974$, a distribution coefficient (slope) of 0.5516. Fig. 6 shows the corresponding software output, $m = 0.552$ – a difference attributable to numerical rounding, confirming that the software correctly reproduces the regression.

Distribution coefficient or slope in log-log graph, m	: 0.552
Angle from x-axis (degree)	: 28.881
Mean size (d50)	: 0.656 mm
Standard deviation	: 0.298

Fig. 6. Statistical parameters calculated by the C&G Circuit Designer (adapted from Rejepov, 2019)

In addition to the distribution coefficient, the software also reports the regression angle, mean particle size (d₅₀), and standard deviation.

3.2. Verification of crushing circuit design results

The crushing circuit generated by the C&G Circuit Designer was then tested against the reference design case (Koyuncu, 2017). For verification purposes, the feed characteristics, particle size distributions, equipment selection criteria, and design parameters reported in the reference design were entered directly into the application. The application was configured for a three-stage open-circuit crushing circuit with screening after each crushing stage. Screen efficiencies of 90%, 95%, and 87% were assigned to the first, second, and third stages, respectively, and the minimum bypass for the closed-circuit parameter was set to 50%, matching the reference design.

The ore properties required for the crushing calculations were entered into the C&G Circuit Designer. These user-defined inputs included the clay content, distribution coefficient, and Bond work index, which influence equipment selection and the crushing calculations. Fig. 7 shows the ore property input interface used in the verification study.

The design specifications were then entered into the application. These user-defined inputs included the maximum feed size of 600 mm. Final crushing product size of 10 mm, feed rate of 200 Mg/h, number of crushing stages, and the crusher type assigned to each stage according to the design reported by Koyuncu (2017). The corresponding design input interface is presented in Fig. 8.

```
***** Ore Properties Required for Size Reduction *****

Clay content (%)                               (Max. 10 %) : 0

Distribution coefficient of ore in feed   (Max. 2 ) : 0.552

Work index (kWh/t)       (Enter 0 if it is unknown) : 14.44
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Fig. 7. Ore property input interface of the crushing circuit designed by the C&G Circuit Designer. (adapted from Rejepov, 2019)

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***** For CRUSHING CIRCUIT *****

Maximum size of run of mine ore before crushing circuit (mm)      (Min. 40 mm) : 600

Final crushing size of ore (mm)                                     (Min. 5 mm) : 10

Feed rate (t/h)                                                     (Max. 1000 t/h) : 200

Enter the number of crushing stage                                (Enter 0 for determination) : 3

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[1] Cone Crusher / [2] Jaw Crusher / [3] Impact Crusher / [4] Roll Crusher

Enter your choice for crusher type

First crusher : 2
Second crusher : 2
Third crusher : 1

Crushing size at first stage (mm) : 150
Crushing size at second stage (mm) : 30
Crushing size at third stage (mm) : 10.00
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Fig. 8. Design specifications and crusher selection used for the verification study (adapted from Rejepov, 2019)

After using the input parameters presented in Figs. 7 and 8, the C&G Circuit Designer automatically drew the flowsheet and performed the corresponding material balance calculations. The results are presented in Figs. 9 and 10, respectively. The Jaw–Jaw–Cone configuration used for this verification case was selected specifically because it matches the reference design case, enabling a like-for-like check of

the mass-balance and distribution-coefficient calculations; it is not put forward as a recommended industrial layout, and it was not generated by the automatic design logic.

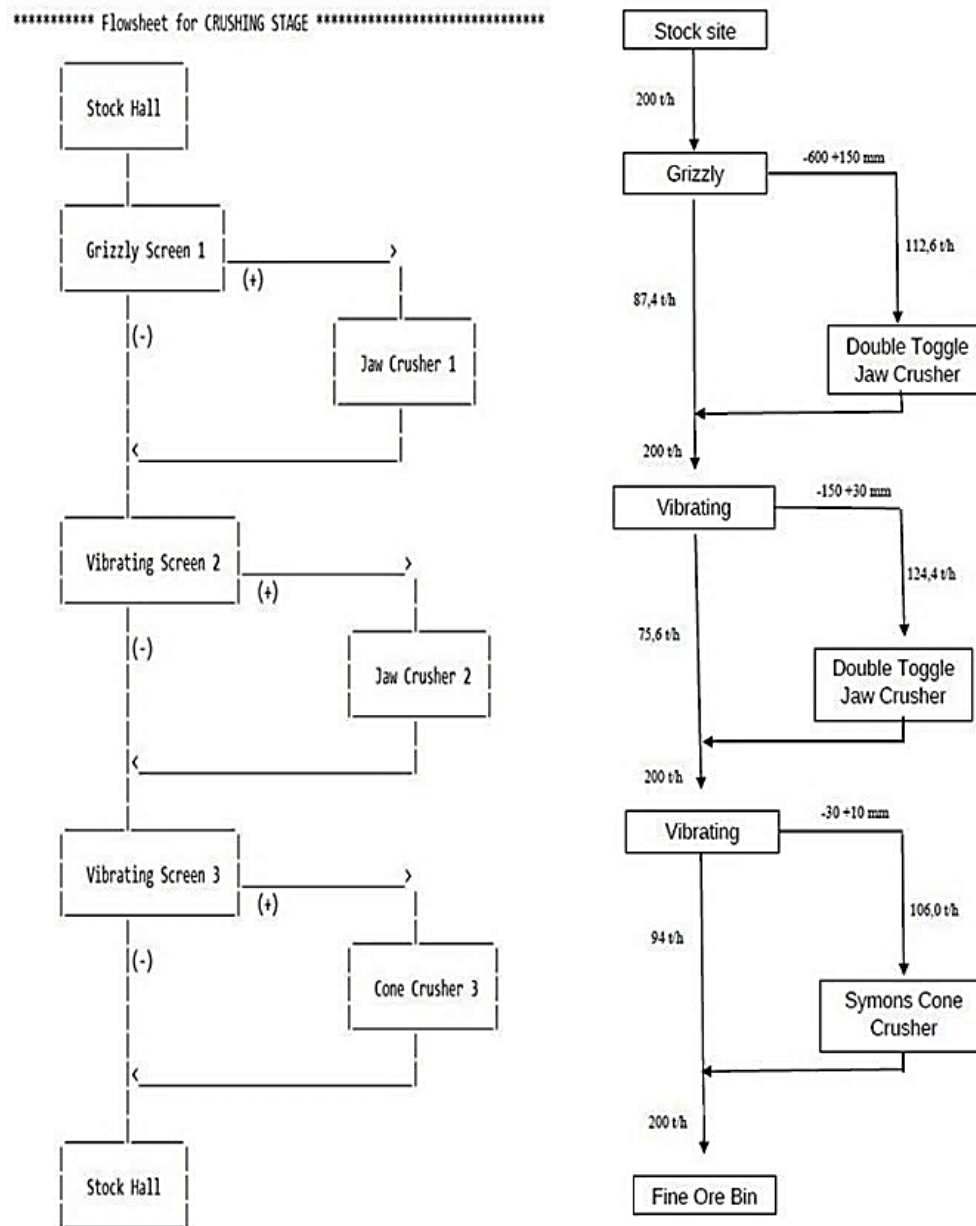


Fig. 9. The crushing circuit designed by the C&G Circuit Designer (left) with the circuit reported by Koyuncu (2017) (right). (adapted from Rejepov, 2019)

To close this gap directly, the automatic design-mode algorithm was subsequently run using the same ore properties as the reference case (clay content 0%, distribution coefficient 0.552, work index 14.44 kWh/Mg) and the same feed size, target product size, and feed rate (600 mm, 10 mm, 200 Mg/h), leaving the number of stages, crusher types, and target sizes for the software to determine. The algorithm automatically generated three crushing stages, consistent with the reference design's overall structure, selecting a Cone-Jaw-Cone crusher sequence with intermediate target sizes of 150, 50, and 10 mm. Both the crusher sequence and the intermediate target sizes differ from the reference design's Jaw-Jaw-Cone sequence and 150/30/10 mm targets; the software reports this as an expected outcome rather than a discrepancy, since at this clay content ($\leq 1\%$) there is no strict technical obligation to select a specific crusher type, and the default per-stage reduction-ratio targets used by the algorithm (4:1, then 3:1) naturally produce a different intermediate size split than the one chosen for the reference plant. Unlike the manually specified case above, the automatic algorithm also closed the final stage, with a

***** Mass Balance for 1st CRUSHING STAGE *****		
For Grizzly Screen 1		
	d100 (mm)	Solid (t/h)
Feed	600.00	200.00
Oversize	600.00	111.61
Undersize	150.00	88.39
For Jaw Crusher 1		
	d100 (mm)	Solid (t/h)
Feed	600.00	111.61
Product	150.00	111.61
***** Mass Balance for 3rd CRUSHING STAGE *****		
For Vibrating Screen 3		
	d100 (mm)	Solid (t/h)
Feed	30.00	200.00
Oversize	30.00	105.12
Undersize	10.00	94.88
For Cone Crusher 3		
	d100 (mm)	Solid (t/h)
Feed	30.00	105.12
Product	10.00	105.12
***** Mass Balance for 3rd CRUSHING STAGE *****		
For Vibrating Screen 3		
	d100 (mm)	Solid (t/h)
Feed	30.00	200.00
Oversize	30.00	105.12
Undersize	10.00	94.88
For Cone Crusher 3		
	d100 (mm)	Solid (t/h)
Feed	30.00	105.12
Product	10.00	105.12

Fig. 10. Stage-wise mass balance results generated by the C&G Circuit Designer for the verification case (adapted from Rejepov, 2019)

reported circulating load of 71.1%, because the default minimum-bypass parameter (10%) is below the bypass fraction of the selected cone crusher (15%). This figure was independently verified by hand from Eq. (2): with $c = 0.4113$, $e = 0.87$, and $b = 0.15$, $R = 142.3 \text{ Mg/h}$, which matches the software's own output exactly. This confirms that the automatic circuit-generation algorithm operates correctly and produces an internally consistent, independently verifiable design for the same ore properties and design criteria as the reference case — though, as expected of a generative design tool applied to a case where more than one crusher sequence is technically valid, it does not reproduce the reference plant's specific, as-built equipment choices.

4. Conclusions

This study presented the development and modernization of the C&G Circuit Designer, a computer-aided engineering application developed to support crushing circuit design. The application integrates particle size distribution analysis, distribution coefficient estimation, equipment selection, and automated circuit generation within a unified computational framework. By combining ore characteristics with established engineering design rules, the application generates crushing circuit configurations directly, unlike most existing comminution software, which primarily simulates, evaluates, or optimizes a flowsheet the engineer has already defined.

The verification against an internal reference case demonstrated that the implemented computational procedures accurately reproduced both the distribution coefficient estimation and the crushing circuit.

The automatic circuit-generation algorithm was additionally exercised on the same reference case's ore properties and design criteria; it produced a different, but technically valid and independently cross-checked, three-stage circuit, which is the expected behaviour of a generative design tool rather than a

discrepancy. This demonstrates the correctness of both the calculation engine and the automatic algorithm for this case, rather than industrial-scale validation more broadly.

Future work will focus on:

- (i) validation against independent industrial or pilot-scale datasets, spanning ore properties and configurations – such as Jaw–Cone and Jaw–Cone–Cone – beyond the single case tested here, and, where possible, a parallel comparison with a commercial simulator such as JKSimMet or USIM PAC;
- (ii) extending the crushing-circuit module to support the reverse-classification configuration already implemented for grinding, and broadening the equipment database with finer crusher sub-type distinctions and additional manufacturer catalogues;
- (iii) incorporating energy consumption models, economic assessment, and multi-objective optimization within the existing modular architecture, without modifying the validated engineering algorithms described here.

These developments will further strengthen the application as a comprehensive computer-aided engineering platform for crushing circuit design.

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