# MINERALPRODUKSJON

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SORTING OF ASYMMETRIC FEEDS USING SERIAL CPE:IPE SORTING CIRCUITS

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ABSTRACT

This study provides a theoretical analysis of the potential capacity enhancement that can be obtained by employing collective particle ejection (CPE) in automated sensor-based sorting circuits when sorting asymmetric feeds. During CPE sorting particles are examined and categorised individually, but physically separated as a set containing several particles. A CPE sorter must be placed in serial connection with a subsequent conventional *individual particle ejection sorter* (i.e. an IPE sorter) in order to achieve complete separation of individual particles, thus creating a CPE:IPE circuit. The relative capacity of this circuit per unit investment cost, compared with a conventional sorting circuit, depends on the relative concentration of the particle categories in the feed and decreases as the particle distribution becomes more symmetrical. As demonstrated in this paper, CPE can yield a significant capacity enhancement per unit investment cost when sorting sufficiently asymmetric feeds in situations where the capacity of conventional IPE sorting is limited by the actual physical separation of the particles and not their presentation and examination or the data analysis. The relative processing period ratio is the key parameter governing the feasibility of the CPE:IPE circuit and must be determined as a function of set size.
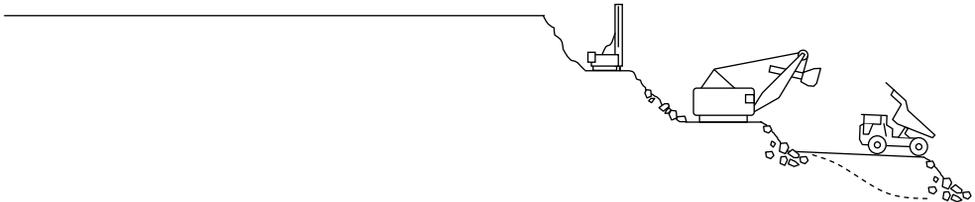
I. INTRODUCTION

In spite of its long history, the revolution in computer technology and the development of fast, accurate and advanced sensors along the entire electromagnetic spectrum, automated sensor-based sorting has still to reach its full potential in the minerals industry. Reviews of sorting technology and the future prospects of modern ore sorters have been compiled and analysed by a number of investigators over the last three decades, including Wyman (1985), Salter and Wyatt (1991), Arvidson (2002), Cutmore and Eberhardt (2002), Manouchehri (2003) and Wotruba and Harbeck (2010). Salter and Wyatt (1991) give a comprehensive overview of the perceived limits to the industrial application of ore sorting and discuss their relevance and accuracy. The process related challenges

aside, low capacity per unit investment cost is perhaps, justly or unjustly, the most frequently used argument against the implementation of ore sorting.

Automated sensor-based sorting can be divided into four sub-processes comprising presentation, examination (i.e. measurement of particle properties), data analysis and physical separation. Even though all four sub-processes must be integrated to form an optimal sorting solution, and each could act as the limiting factor with respect to capacity and separation efficiency, most attention by far has been given to the examination step and the development and application of new sensors. A vast range of sophisticated measuring principles have been suggested in addition to the basic photometric or optical techniques using colour scanners or cameras. In their 1991 review of sorting technology Salter and Wyatt listed the following possible examination principles: Raman spectroscopy, FTIR, laser and glow discharge spectroscopy, scanning electron microscopy, Auger, SIMS, XPS, x-ray diffraction and fluorescence, gas and ion chromatography, mass spectroscopy, thermal analysis, inductively coupled plasma and atomic adsorption spectrometry, neutron activation analysis, radon and radioactivity measurements, particle size analysis and various electrochemical techniques. Since the early 1990s the feasibility of more and more of the techniques on this list have changed from theoretical to practical and still more techniques have been added (Wotruba and Harbeck, 2010). However, the practical application of ore sorting in the mineral industry is still dominated by photometry or the use of natural radiation sensors.

Considering the last few decades' exponential growth in data processing power and the continuing development of sensors with higher and higher acquisition speeds, the number of potential applications where the actual mechanical separation of the individual particles will represent the capacity limiting step is likely to increase. Obviously, more attention should be devoted to the development of low cost, highly efficient ejection systems. However, shifting the rate limiting step from examination to separation should also spur a closer evaluation and analysis of the fundamental algorithms on which the sorting process is based. As will be shown in this paper the concept of *collective particle ejection of individually examined particles* could offer a significant increase in capacity per unit investment cost when processing sufficiently asymmetric feeds (i.e. feeds dominated by one category of particles). Alternatively, the potential capacity enhancement could allow for a slower but cheaper separation solution (in terms of both investment and operating costs).

The concept proposed in this paper has limited applicability as it is by its own nature restricted by the composition of the feed and would require modified technical solutions for particle presentation and separation. However, given a case where these conditions are satisfied, the increase in capacity per unit investment

cost could be economically significant and would as such contribute to extending ore sorting to new applications. With this in mind, the scope of this paper is to demonstrate the concept's potential by investigating the relative capacity enhancement per unit investment cost (i.e. relative to a conventional sorting circuit) rather than its technical implementation.

2. THE CPE:IPE CONCEPT

The sorting concept described in this paper is, for lack of a better phrase, referred to as collective particle ejection sorting (i.e. CPE sorting). The working principles of a CPE sorter are identical to those of a conventional sorter up until the actual separation step except for the fact that the particles are presented in discrete sets (i.e. a limited number of closely spaced particles). The particles are still being examined and categorised according to the separation criterion as individual entities. During the separation step each set is rejected or accepted as a single unit based on its composition of categorised particles. The particle sets are defined by their set size s, a parameter that simply describes the number of particles in the collection. Consequently, conventional sorting, hereby referred to as individual particle ejection sorting (i.e. IPE sorting), can be regarded as a special case of CPE sorting with a set size of 1.
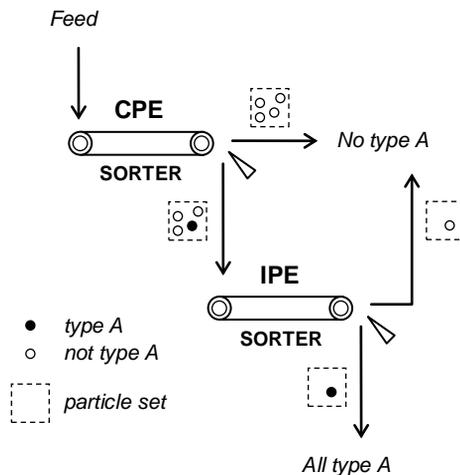
Figur 1. The serial CPE:IPE circuit processing a feed dominated by 'not type A' particles.

Since a CPE sorter separates particle sets rather than individual particles it must be combined with a subsequent IPE sorter in order to achieve complete separation. When the sorting criterion defines two particle categories and the CPE sorter is able to produce two different products, particle sets consisting exclusively of particles belonging to the predominant category would report to one product, while sets containing both particle categories would report to another. As illustrated in Fig. 1, the latter product would then be processed by a conventional IPE sorter. It is important to note that the particles subjected to CPE sorting are still identified and categorised on an individual basis according to the same preset sorting criterion used for the IPE sorting. Hence, despite the fact that the particles are not physically separated on an individual basis, CPE sorting is fundamentally different from bulk sorting where the evaluation is based on parameters (particle averages) describing the set as a whole. Bulk sorting offers simpler ore handling and higher throughput, but has the disadvantage of less discrimination in ore selection.

As will be shown in this paper, the concept of CPE pre-sorting illustrated in Fig. 1 could offer enhanced overall capacity per unit investment cost provided that the following conditions are satisfied:

1) The capacity of the IPE sorter is limited by the rate of physical separation (i.e. particle ejection) rather than particle presentation, examination and data analysis.

2) The feed is sufficiently asymmetric, i.e. it is dominated by one type of particle.

In order to utilise CPE the feed particles should be presented in sets with sufficient distance on the separator belt between each set to allow effective separation. As opposed to IPE where such a distance is required between each individual particle CPE only requires sufficient spacing between the particles in the same set to correctly identify and categorise them as individual particles. Hence, if the first condition is satisfied, the CPE sorter would be able to process a higher number of particles per unit time than the IPE sorter due to a shorter average inter-particle distance of the feed.

The second condition is a result of the fact that the gain in capacity obtained from utilising a CPE pre-sorting step decreases as the feed becomes more symmetric. When processing a near symmetric feed the majority of the particle sets will contain both particle categories and will as such have to be processed by the IPE sorter anyway (as shown in Eq. 1). Moving towards more symmetric feeds a point will be reached where the marginal capacity gain obtained by CPE pre-sorting fails to justify the investment.

When assessing the capacity per unit investment cost of the proposed CPE:IPE circuit it could, as a starting point, be compared to a circuit consisting of two parallel IPE sorters. It is reasonable to assume that these two alternatives would represent roughly similar investment costs as they rely on the same number of sensors, data processing units and physical presentation and separation systems. However, the CPE:IPE circuit holds a potential for further capacity enhancement per unit investment cost if the information obtained during the pre-sorting step can be utilised by the subsequent IPE sorter. If the order of the particles that have been categorised by the CPE sorter can be preserved until they are fed to the IPE sorter, the latter sorting step simply becomes a matter of identifying the position of the already categorised particles prior to the physical separation. This would require some engineering with respect to the ejection system of the CPE sorter, but it would allow for the use of a very simple (i.e. inexpensive) optical sensor during the subsequent IPE step. Alternatively, the CPE sorter could 'tag' the particles (e.g. by using an ink jet) thus eliminating the need to keep the particle order undisturbed. When the sorting criterion relies on the use of expensive advanced sensors, either option would reduce the investment cost by limiting the need for these sensors to the pre-sorting step alone. Hence, in the extreme (and unlikely) case where the cost of the advanced sensors completely dominates the investment costs the capacity of the proposed CPE:IPE circuit should be compared to that of a single IPE sorter.

3. MODELLING AND ANALYSIS

3.1 Derivation of an expression for relative capacity

Consider the CPE:IPE circuit shown in Fig. 1, where a CPE sorter with a fixed set size s operates in serial connection with a subsequent IPE sorter. Assume that the individual particles of the original feed can be classified according to a preset definition as either 'type A' or 'not type A'. Let x represent the number fraction (i.e. the concentration) of 'type A' particles in the feed to the CPE sorter and assume further that 'type A' defines the minority category. According to this definition x is always smaller than or equal to 0.5. The fraction of the total feed that still needs to be processed by the IPE sorter is then given by:

$$\gamma = 1 - (1 - x)^s \tag{1}$$

This is easily derived from the fundamental laws of probability, as the fraction γ is equal to the relative number of selections that only contain 'not type A' particles.

Assume that the CPE sorter is fed at a constant feed rate. Let t_s represent the processing period for a single set of size s processed by the CPE sorter. The

processing period can be defined as the average time interval between the separations of two consecutive sets. Hence, the inverse of this value represents the total number of sets processed per time unit. Correspondingly, let t_1 represent the IPE sorter processing period for a single particle (i.e. the processing period for a set of size $s = 1$). Since the sorter is fed at a constant rate both t_s and t_1 can be assumed to be constants.

The two sorters operate in a serial connection and either could in theory act as the capacity limiting step. As the IPE sorter only has to process the fraction γ of the original feed (i.e. the feed entering the CPE sorter) it follows that the overall capacity of the circuit is limited by the capacity of the IPE sorter only when:

$$\gamma t_1 > \frac{t_s}{s} \tag{2}$$

As shown by Eq. (1), this condition is also a function of x. Consequently, by combining Eqs. (1) and (2), the IPE sorter represents the capacity limiting step when:

$$x > 1 - \left(\frac{s - \tau}{s} \right)^{\frac{1}{s}} \tag{3}$$

where τ, the relative processing period ratio, is defined as:

$$\tau = \frac{t_s}{t_1} \tag{4}$$

Hence, the concentration of 'type A' particles in the original feed that will produce capacity equilibrium between the two sorting steps is given by:

$$x_E = 1 - \left(\frac{s - \tau}{s} \right)^{\frac{1}{s}} \tag{5}$$

The overall capacity of the CPE:IPE circuit, in terms of the number of *original feed particles* processed per unit time, can then be expressed as:

$$C_{CPE:IPE} = \frac{s}{t_s} , \quad \text{when } x \leq x_E \tag{6.a}$$

$$C_{CPE:IPE} = \frac{1}{\gamma t_1} , \quad \text{when } x > x_E \tag{6.b}$$

In comparison, the overall capacity of a single IPE is simply given by:

$$C_{IPE} = \frac{1}{t_1} \tag{7}$$

To facilitate easy comparison, the *relative* capacity per unit investment cost of the proposed CPE:IPE circuit can be defined as:

$$\theta = \frac{C_{CPE:IPE}}{\lambda \cdot C_{IPE}} \tag{8}$$

Here, the factor λ determines the basis of comparison in terms of the number of IPE sorters that could be purchased for the same investment cost. As explained in chapter 2, the value of λ could vary between 1 and 2 (2 being a far more likely value and 1 being the 'theoretical limit'). Combining Eqs. (1), (6), (7) and (8) will then yield:

$$\theta = \frac{s}{\lambda \tau} \ , \qquad\qquad \text{when} \ \ x \leq x_E \tag{9.a}$$

$$\theta = \frac{1}{\lambda - \lambda (1-x)^s} , \qquad \text{when} \ \ x > x_E \tag{9.b}$$

The proposed CPE:IPE circuit will represent an improvement in overall capacity when $\theta > 1$. When $x > x_E$ the function $\theta(x)$ is continuously decreasing (see Eq. (9b)). When $x \leq x_E$ the relative capacity is not a function of concentration (see Eq. (9a)) and θ is at its maximum. It is also clear from Eq. (9.a) that $\theta \geq 1$ implies that $s \geq \lambda \tau$. Hence, as long as the latter condition is satisfied, x_c given by Eq. (10) represents the critical concentration of 'type A' particles in the original feed (i.e. the upper concentration limit) with respect to the useful applicability of the CPE:IPE circuit.

$$x_C = 1 - \left(\frac{\lambda - 1}{\lambda} \right)^{\frac{1}{s}}, \quad \text{when} \ s \geq \lambda \tau \tag{10}$$

When $x \geq x_C$ the feed is too symmetric to benefit from CPE pre-sorting.

3.2 Exploring the relative capacity function
As shown is section 3.1, the relative capacity of the CPE:IPE circuit is easily determined once the set size s and the relative processing period ratio τ is given. As a starting point, the value of τ could be assumed to be close to 1 since the

processing periods are largely governed by the response and return time of the ejection system and not the number of particles that are ejected during each separation. However, depending on the engineering solution, larger sets could require higher values for τ. Fig. 2 presents the relative capacity of the CPE:IPE circuit per unit investment cost as a function of x for different values of s at $\tau = 1$ and $\lambda = 2$, whereas Fig. 3 exemplifies how the relative capacity depends on the value of τ for a fixed set size $s = 4$. In practice, the exact relationship between s and τ should be determined for the actual sorter in question.
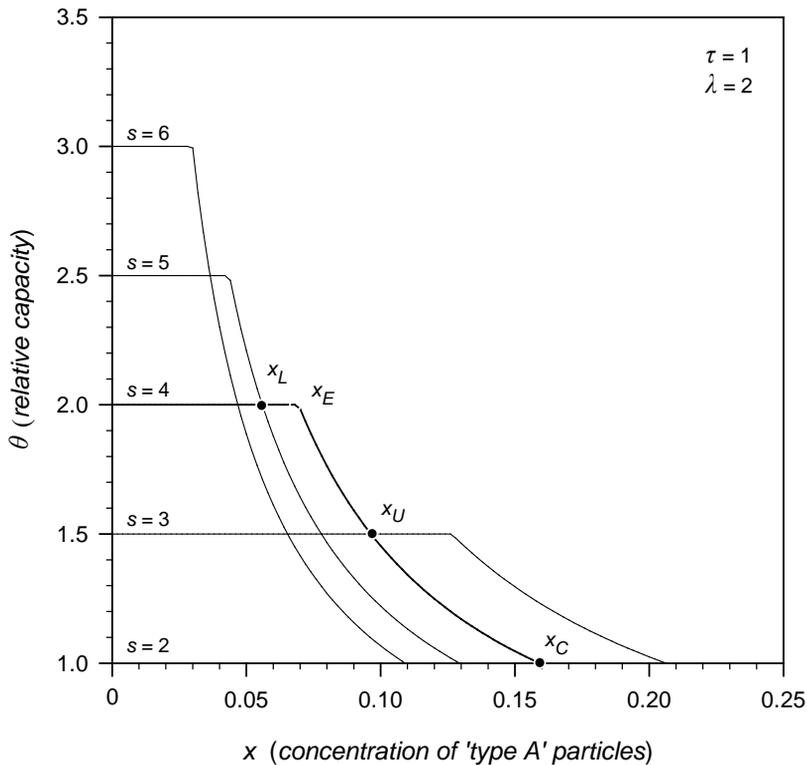
Figur 2. Relative capacity as a function of x and s at $\tau = 1$ and $\lambda = 2$. The characteristic concentrations x_E, x_C, x_U and x_L (See Eqs. 5, 10, 11 and 12, respectively) are shown for $s = 4$.
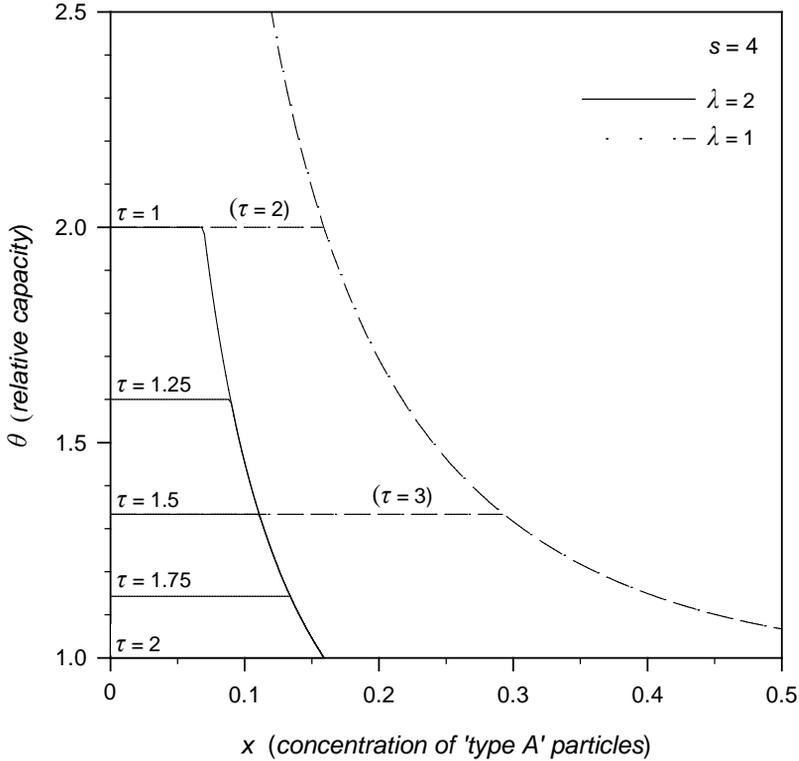
Figur 3. Relative capacity as a function of x and τ at s=4.

Figures 2 and 3 demonstrate the relative capacity's strong dependency on concentration when the latter grows larger than x_E. The maximum capacity for a given set size is achieved in the concentration range where the CPE sorter is the capacity limiting step (i.e. $x \leq x_E$). In this region the relative capacity is independent of concentration. From a practical point of view, it is necessary to determine the optimal set size for a given concentration. As can be seen from Fig. 2, the concentration variable can be divided into discrete intervals; each with their own optimal value of s. Equating Eq. (9.a) using a set size of $s-1$ with Eq. (9.b) with a set size of s will yield the following upper concentration limit for s as the optimal set size:

$$x_U = 1 - \left(\frac{(s-1) - \tau}{(s-1)} \right)^{\frac{1}{s}} \tag{11}$$

The corresponding lower limit x_L is easily found since $x_L(s) = x_U(s+1)$:

$$x_L = 1 - \left(\frac{s - \tau}{s} \right)^{\frac{1}{s+1}} \tag{12}$$

Table 1 summarises the information found in Fig. 2 by presenting the characteristic concentrations x_E, x_C, x_U and x_L and the maximum relative capacity $\theta(x_E)$ as a function of set size for $\tau = 1$ and $\lambda = 2$.

Table 1. Characteristic concentration and maximum relative capacity for $\tau = 1$ and $\lambda = 2$.

s	2	3	4	5	6
x_E	0.293	0.126	0.069	0.044	0.030
x_C	0.293	0.206	0.159	0.129	0.109
x_U	-	0.206	0.096	0.056	0.037
x_L	0.206	0.096	0.056	0.037	0.026
$\theta(x_E)$	1	1.5	2	2.5	3

Note that x_E, x_U and x_L are independent of λ but depends on τ, whereas x_C is independent of τ (provided that $s \geq \lambda\tau$ so that x_C is defined), but depend on λ. The maximum relative capacity (i.e. $\theta(x_E)$) at a given set size is simply proportional to $1/\lambda\tau$. Hence, as shown in Fig. 3, halving the value of λ from the default value of 2 would double the relative capacity of the circuit.

3.3 Practical applications and theoretical limitations

The useful applicability of the CPE:IPE concept is limited by its underlying premise; i.e. that the capacity is not limited by presentation, examination or data analysis, but by the actual physical separation of the particles. In other words, the average amount of time required to correctly categorise a single particle and relay the information to the ejector system must be lower than the processing period t_s divided by the set size s. In practice, the function $t_s(s)$ (and consequently $\tau(s)$) will very effectively limit the value of s and the potential gain in relative capacity. However, even $s = 3$ would yield a significant gain provided that the feed is sufficiently asymmetric and τ is not too large. Using this set size the maximum capacity increase of 50% at $\tau = 1$ is attainable up to $x = 0.126$, whereas $\tau = 1.25$ offers a maximum increase of 20% up to 0.164.

The practical feasibility of the CPE sorting concept hinges on the relative processing period τ which is a function of the technical solutions on which the sorter's ejection system is based. As argued earlier in this paper, small set sizes could offer t_s values close to that of t_1, thus yielding a τ close to unity. This is likely to be the case for the sorting of coarse particles where mechanical ejector systems (e.g. mechanical flaps) are used rather than air nozzles to achieve physical separation. Mechanical ejector systems require less energy during operation, but

are slower than air nozzles and are replaced by the latter when the feed particle size becomes too small for the mechanical systems to handle efficiently. This offers an alternative scope for the proposed CPE sorting concept as it could equally well be used to extend the useful size range of mechanical flaps by trading the potential capacity enhancement for lower energy costs during operation as well as reduced investment costs.

As stated in the introduction and emphasised further in chapter 2 the proposed CPE:IPE circuit would require modified technical solutions for particle presentation and separation. A variety of different implementations would be possible and cost-efficient elements could probably be adapted from packing and sorting machines utilised in the food Industry. However, discussing the design and construction of such systems are beyond the scope of this paper.

4. CONCLUSIONS

The following conclusions can be drawn from the theoretical analysis comparing the concept of *collective particle ejection sorting* (i.e. CPE sorting) of particle sets containing several particles with conventional *individual particle ejection sorting* (i.e. IPE sorting):

1) CPE can yield a significant capacity enhancement per unit investment cost when sorting sufficiently asymmetric feeds in situations where the capacity of conventional IPE sorting is limited by the actual physical separation of the particles and not their presentation and examination or the data analysis.

2) A CPE sorter must be placed in serial connection with a subsequent IPE sorter in order to achieve complete separation of individual particles. For a given set size, as long as the relative concentration of particles belonging to the minority category is sufficiently low the capacity of this circuit (i.e. the CPE:IPE circuit) is limited by the CPE step. When this is the case the capacity is at its maximum level and does not depend upon the concentration.

3) The relative processing period ratio is the key parameter governing the feasibility of the CPE:IPE circuit and must be determined as a function of set size.

4) The relative capacity per unit investment cost of the CPE:IPE circuit can be further enhanced if the information obtained during the CPE step can be

utilised by the subsequent IPE step, thus omitting the need for a dual set of advanced sensors.

5) CPE can be used to extend the useful size range of mechanical flaps by trading the potential capacity enhancement for lower energy costs during operation.

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