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Simulation of Coal Preparation Plant by using the Simulation Packages “Limn – The Flowsheet Processor”

Bachelor Thesis

by

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1 Introduction

In this chapter, the research objectives are presented with an outline of general background, the objective and the scope required to accomplish the consequences of the research.

1.1 General background

Coal is the most vital source of energy in the world. 27 percent of the global energy consumption is generated by using it as of 2017 (Figure 1) (1).

Figure 1. Total global energy consumption

Coal preparation, a procedure that removes the residual materials or elements, such as ash and pyritic sulfur, from mined coal (2), of the ore to increase the economic value of it and results in a higher-grade product, plays a vital role in the total coal consumption value chain. Coal has two primary final end uses: (1) thermal coal used to generate electricity, and (2) coking coal used as a feedstock for steelmaking (3).

Moreover, undesirable surface moisture impedes coal utilization by reducing heat value, increasing transportation costs, and creating unnecessary approach problems. In total, these contaminants constrain downstream use and diminish the value of the raw material (3). As a consequence of the issue, the main purpose of coal preparation is to maximize the yield by separating the coal from the waste contaminants prior to purchase to the end consumer.

The price and market demand can result in more advanced infrastructure and output that are seen in most of the coal mines and processing plants in Mongolia today. The mining operations mainly consist of large opencast operations and enormous underground expansions to allow customer demand. In return, the processing plants are becoming more superior in operation and control to minimize losses of coal product produced.

However, an advanced look at the total coal consumption value chain is essential with increased global environmental awareness and demands on the fossil fuel industry as a whole. The export market for coking coal could narrow down in the future as a result of the growth and demand for alternative energy sources globally such as nuclear, gas, wind, and solar applications.

Therefore, the resource management should be improved, and sustainable processing is needed without affecting the environment, and the determining factor should be near to constant due to exhaustible resources, in particular, water, required for coal preparation plants available in Mongolia.

Mongolia is rich in coal resources, which provide 90 percent of all consumed energy at the moment. The previous studies have explored that hypothetical resources of Mongolian coal are estimated to be 152 million tons with 10.15 billion tons of it are identified reserves (4). Mongolia has extracted 26 million tons of coal as of July 2018.

The mining sector, especially coal mining, remains a dominant part of Mongolia's foreign trade and exports. In 2017, China imported 271 million tons of coal, and it is cooperating with many countries in coal market including the USA, Australia, Russia, and Mongolia (5). Mongolia exports mostly coking coal, used for metallurgical and steel industries, to China, which produces 50% of the world's steel consumption alone.

1.2 Problem statement

Coal plays a dominant role in Mongolia's economy. Despite coal export, which has been constantly growing over the last three years in Mongolia (from 15 million tons in 2015 to 21 million tons in 2018) (5), the coal importers are facing the challenge of improving their technologies and coal quality.

Fundamental principles and an understanding of the production processes is required to develop them. It should, therefore, be described more in detail on the below.

The raw coal quality is dependent on the coal seam. Therefore, coal as a feed goes to the plant in a different range of coal quality and coal capacities. Later the coal can be put into the plant or can be stored onto a stockpile.

The coal on the stockpile must be handled again and fed to the ROM section if needed. Subsequently, the coal can go to a coal handling plant or a blending yard, where coal is separated based on the quality and combination of coal seams. The coal, which fed to the ROM section, is crushed in three stages from a top particle size of 500 mm to a 50 mm size. Upon entering the plant, the coal is separated into three different size grades to allow optimal recovery of each coal size.

Beneficiation process removes coal impurities through dense medium separation and gravity separation methods.

Income will rise with the increasing volume of product generated at detailed quality requirements from consumers:

i. Maximization of the product yield achieved in the coal preparation plant (CPP);
ii. Due to the nature of coal existence, each seam of coal has to have an individual wash curve and separation density;
iii. The value can, therefore, be performed by yield optimization, while reaching quality specification of consumers;
iv. Coal must be blended uniformly in a blending yard; and
v. Thereby, operational costs can be reduced. Since higher yields produce larger product quantities, it will support the revenue achieved since product sales can be increased.

Moreover, the rejects from a CPP can affect the air and water quality, land usage, and have a negative impact on human health and safety. Thus, constructing the CPP without good plan has a lot of problems even including many costs.

Given a greater understanding of the coal mining process, more expected product yields can be obtained by solving complex decision-making requirements that optimize the coal plant yield. Therefore, the following research questions should be answered in this study:

- What is the optimal coal washing approach that will maximize yield whilst satisfying consumer quality requirements?
- What characteristics will the model cover that considers all system and plant limitations?

1.3 Research objectives

The simulation of coal preparation plant (CPP) plays an important role to ensure the optimal exploitation and use of coal within the country. The approach of coking coal demand has led to a new dimension of possibilities to the Mongolian coal industry. Mongolia's coking coal can be processed more efficiently and cost-effectively by simulating the CPPs with different types of separation equipment. Moreover, simulations of the CPP are also used for the difficulty level of washing coals, the impact of using different separation equipment on the yield and its estimation by using software LIMN which processes the flowsheet.

1.4 Clarification of key concepts and terminology

Key concepts are defined and explained. The definitions include:

i. Run-of-mine coal (ROM):

It is raw and unprocessed coal and comes directly from a mine.

ii. Coal preparation plant (CPP):

A CPP consists of a set of equipment which allows separation of concentrate and tails. In the CPP, dense medium separation and gravity separation is typically used to enable higher energy values of concentrate.

iii. Coal handling and preparation plant (CHPP):

The CHPP is made up of coal crushing equipment and conveyor systems that is needed to prepare the coal before the washing process. It also includes product handling equipment, stockpile areas, product blending infrastructure, train loading equipment and discard handling facilities.

iv. Coal blending yard:

In order to achieve a homogenized coal, a coal blending yard which allows ROM coal of two or more different grades or seams to be stacked is needed.

v. Coal washing process:

This is a process that occurs within the CPP. It uses principles of dense medium separation and gravity separation to separate discard particles from product coal particles.

vi. Plant yield:

The plant yield can be determined the ratio of the percentage of product that is formed and is measured relative to the amount of feed that entered the coal processing plant.

vii. Washability table:

It is a data recording table that shows the quality parameters of the coal sample controlled by laboratory processes that separated the sample at increasing density intervals. At each density, the laboratory notes the ash and calorific value, achieved as well as the yield percentage done at the specific density used.

1.5 Coal preparation plant fundamentals

Coal preparation is the process of ROM coal which is made into a clean and graded product suitable for the market. Coal preparation includes physical processes that upgrade the quality of coal by adjusting its size and reducing the content of mineral matter. Coal preparation is freely defined by five distinct unit operations: size reduction, size separation, solid separation, solid-liquid separation, and waste disposal (3).

The CPP crushes the as-mined coal and reduces the particle size from an average of 300 mm to less than 75mm (6). Sizing screen classifies then the crushed coal into four different size fractions (see **Error! Reference source not found.**).

Table 1. A general guide to coal sizing and treatment processes of each coal size

Size grade description	Size, mm	Treatment process
Coarse	+10	Dense medium bath separators
Intermediate	10 x 0.5	Dense medium cyclones
Fine	0.5 x 0.15	Spiral concentrators
Ultra-fine	0.15 x 0	Slimes dam

CPPs include a simple crushing operation as well as generally include complex circuits cleaning the entire size range of feed coal to reject the most parts of impurities involved with ROM material. While gravity concentration such as dense-medium vessels, dense-medium cyclones, and jigs is the major cleaning method for coarse and intermediate coal size fractions, flotation is the optimum cleaning method for fine size fractions.

2 Literature Review

2.1 Introduction

The aim is to analyse the information and data gained and to identify the proper argument when advancing a plant simulation.

Simulating the CPP is an extremely complicated problem, due to the behaviour of many variables that influence the plant performance and yield output. Generally basic principles must see as costs and optimization method in any manufacturing industry, even CPP; however, they are complex factors to assess. The tails from a CPP affect the air and water quality, land usage, and have a negative impact on human health and safety. Therefore, both plant yield optimization and economic analysis of coal preparation processes must be encompassed in the design process. Furthermore, selecting equipment that will maximize the yield is important.

2.2 Coal preparation plant efficiency

Coal can be washed or crushed, depending on the plant performance. The performance of a coal preparation operation is influenced by three factors, such as the raw coal, characteristics of the cleaning unit, and market considerations (7, 6). Efficiency criteria must be advanced to describe the effect of the nature of the coal, and the essential characteristics of the cleaning unit. Moreover, no commonly accepted efficiency coefficient exists at the present time (7). Without considering this issue, there are acquired efficiency criteria linking to the effect of both the coal and the cleaning unit that will be discussed with the perspective of using these efficiency criteria in the computer model or simulation software program.

2.2.1 Effect of Raw Coal

Walters, Ramani, and Stefanko (7) have mentioned that the most common criteria to describe performance is the recovery efficiency in their research. It is formulated to express the yield of washed coal as a percentage of the yield of float coal known to be in the feed by the washability analysis;

$$Recovery\ efficiency = \frac{Actual\ yield\ of\ washed\ coal}{Theoretical\ yield\ at\ the\ same\ ash} * 100\%$$

2.2.2 Effect of cleaning unit

2.2.2.1 Characteristics of calculating cleaning unit efficiency

Other criteria to measure the efficiency of CPP’s cleaning units such as jigs, concentration tables, dense medium separators, is the distribution curve which was developed by Tromp, and so-called partition curve (7, 8).

In a two-product separation, a raw material, being the mixture of particles with different properties, is divided into two components based on different physical properties such as density or size, etc. Sanders (8) defined it as “a curve, which gives as a function of physical properties or characteristics, the proportion where the different elemental classes of raw feed having the same properties split into separate products”.

In general, the slope of partition curves is dependent on particle size and the cut point of separation. The efficiency decreases with decreasing particle size and increasing cut point whereas ‘Probable error (Ep)’ increases (8, 9). For this reason, the partition curve reflects the characteristics of a cleaning unit.

Cut point is defined as the relative density of the material which divides equally between the two products. At this relative density, therefore, the partition coefficient is 50% which is so-called partition density and known as D_{50} (8).

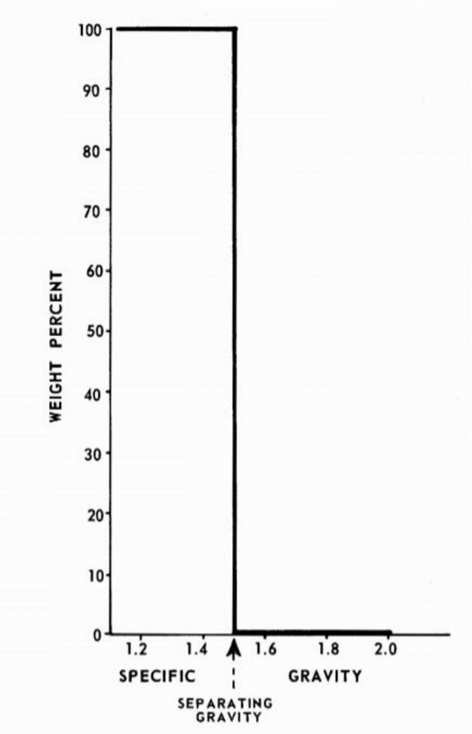


Figure 2. A partition curve with a perfect separation at SG=1.5

In general, the cut point can be controlled by variation of an operational control in the plant or by means of physical adjustment to the equipment. Dense-medium separators are set by controlling the medium density and the separation density (9).

By measuring the actual plant yield and carrying out float-and-sink analysis on the products, the partition curve can be produced. On the contrary, if the partition curve is known, the plant yield and product quality can be predicted. A perfect separation would have a partition curve as shown in Figure 2.

The deviation of the curve from the “perfect separation” curve gives a measure of the efficiency of the cleaning unit. The error area and the probable error have been developed for measuring this deviation. The error area, however, is not suitable to calculate, and the probable error is the most acceptable efficiency criteria.

Probable error

Terra introduced the concept of probable error which is defined as half the relative density difference between the 75% and 25% partition values. The steeper the partition curve, the lower the probable error.

$$Ep = \frac{D_{75} - D_{25}}{2}$$

Probable error as a measure of performance of a cleaning unit has its disadvantages.

- In the curve, the tails are not adequately described. As a consequence, it is typical for manufacturers of cleaning equipment to provide a complete partition curve, as well as probable error figures. Due to this, the purchaser can measure the impact of tails on the separation.
- This criterion is dependent of the specific gravity of the separation.

In order to develop the criterion of sharpness of separation, that would be independent of the specific gravity of the separation, therefore, imperfection which is symbolized “I” should be introduced. Cerchar mentioned that imperfection is a constant for a particular cleaning unit. More specifically, imperfection does change with different types of cleaning unit.

2.2.3 Economics of yield optimization

In preparation plant design, application of analytical methods to reach an economic optimum has not been given as much consideration as have other areas of coal preparation. It is necessary to know the market value of the coal at different quality levels to arrive at the optimum conditions. It is crucial to understand at the planning stage how a distinct cleaning unit will operate on specific coal, what gravities to operate different units at, and what will be the economic consequences resulting from yield losses caused by:

- changes in the characteristics of the coal;
- the inefficiency of the cleaning units; and
- incorrect separating gravities.

If the quality of raw coal complies with the expected market specification, only crushing is needed. This term is called bypass coal. The coal that is only crushed and not washed will yield higher product recoveries (6).

2.3 Approaches of previous studies

Numerous studies have been conducted in the past to determine a procedure that maximizes the overall plant yield.

To maximize the yield of clean coal at the desired ash content, Sarkar, Sakha, and Lahiri (10) suggested a graphical approach, in particular, cleaning of coarser coal at a higher ash content and finer coal at a relatively lower ash content result in the best yield while meeting the given ash constraint.

Walters et al. (7) developed a computer-based plant optimization model where the gravity separation of the fine coal remains constant while the separating gravity of coarse coal rises gradually until the desired product quality is reached.

King (9) developed graphical and numerical techniques to optimize the yield of a plant at a given product quality constraint. Graphical methods were operated on the basis of the partition curve to determine the optimum cut points of separation.. He stated that the potential loss of yield that can occur when a plant is established without considering the optimal combination of cut points (9). These graphical approaches have limited application in a large combined circuit operating in the plant since they deal with many density fractions involving very complex calculations and difficult interpolations.

The split of cleaning and dewatering approach has significantly enhanced the overall efficiency of the coal preparation process; however, the use of parallel circuits requires plant-wide optimization to maximize yield and desired ash values. Several have suggested innovative approaches that utilize incremental ash, specialized blending, and genetic algorithms to identify optimum operating conditions (11, 12).

All the previous studies have determined the certain optimal condition as a result of one quality which is ash assay or sulfur assay. The suggested condition was recommended to balance the incremental product quality for each circuit to get the optimum yield.

Throughout the approaches studied before, computer applications fit further research or the thesis. Most of the applications can be divided into two categories: linear programming models, and computer simulation models.

Linear programming techniques have been applied in the planning of coal preparation design (2). Wright concluded that linear programming is only useful depending on how much of a problem actually exists in choosing the products to be created.

Besides, King (9) recommended that simulations should be based on the following combination of set points: dense-medium bath 1.35, dense-medium cyclone 1.65 and the water-only cyclone 1.95.

2.4 Simulation of a coal preparation plant

2.4.1 Nature of simulation

Computer simulation has been a contemporary field of research since the 1960s (13), and a great deal of good work has been done to make simulation into a feasible and practical tool. A simulation is a procedure that can be used to model any process rather than running it in real time (7, 6). It can expose many aspects of plant performance without operating plant itself under experimental conditions too (4). The model will, therefore, describe the system itself and the simulation will represent the operation of that system over a specific time (6). There are several ways where simulation can be achieved, especially by a digital computer which is programmed to simulate the behavior of the actual plant and can provide a description of what the plant will do and how it will perform under a variety of circumstances.

Owing to the feed that affects mass balance, medium balance, and water balance outputs, a system of CPPs is complex (6). Simulation is only possible when a detailed understanding of each component of the system has been achieved. It provides a tool for the prediction of system behavior even if the system does not exist in reality (4, 7). The modelling techniques try to build a quantitative description of the operating behavior of the equipment in terms of underlying physical and chemical principles that rule their operation. To be useful and effective in the simulator, the models must fit logically together so that the simulator can function in an intended way. Different models for the same unit operation must also be interchangeable to facilitate their comparison under comparable operating conditions. The simulator must be provided with an accurate description of the feed that is to be processed, a description of the flowsheet that illustrates the process, and a description of the operating behavior of each clean operations that are included in the flowsheet (13). Designation of all coal plants is based on solid flows the equipment sizing to support efficient separation (14). These will be explained the following sections more in detail.

2.4.2 Available simulation programs

Research conducted by Hand and Wiseman (14) supports the concept of LIMN as a suitable program to simulate a CPP. As a result of this research, LIMN is a very effective simulation tool where various feed options could be tested and simulated with high accuracy.

In simulation packages for coal plants such as LIMN, important stream information such as mass flow, volume and density are demanded as part of the CPP simulation. In this model, the mass balance of the plant considers the following characteristics: coal size and its density, discard solids with different size and various density, magnetite flow, and process water flow requirements (14). LIMN was used to simulate a closed circuit mineral processing operation in another common mineral processing application as well (6).

Other available software, ModSim, is used for a simulation of ores, coupled to milling and flotation separation processes. Although the software is not typically used to deal with coal plant simulations (6). The significant drawback of ModSim is that it has limited capability to predict the performance of dense medium separation in the CPPs.

Aspen Plus coal plant simulation program is relatively expensive and is suitable for simulation of CPPs where sulfur and ash reduction are required. The software can detect the effect of different feed options; however, the medium and flow balances cannot be predicted, and only solid balances can be simulated (6). Moreover, it has limitations to predict the performance of separation equipment in a CPP. From these major limitations, the software does not fit for this study.

In conclusion, the past findings indicated that the simulation packages should be evaluated and ranked to select the appropriate software tool depending on different scenarios or processes.

2.4.3 The simulation requirements

The plant simulation should at least consider the feed quality and design limits of the coal flow circuit and the quality requirements of customers. The main aim of the simulation is to predict the plant yield, quality and possible bottlenecks within the coal plant for each feed option. Based on the plant operating density, and plant design limitations and feed type, the yield, and quality achieved for the product are dependent variables.

2.4.4 Plant feed data preparation for the simulation

For a complete washing plant design, wet screening data is preferred for CPP flowsheet selection. Using dry screening data directly would underestimate the amount of fines going to the fine circuit. As a result, the fine circuit of the CPP may be greatly undersized. Dry screening also changes the washability of both the coarse and fine size fractions due to the presence of fines in the coarse coal (15).

2.5 Conclusion

Designing and building a coking CPP based on coal size and washability data is very challenging. The problem lies in the evaluation of representative plant feed coal data, the comparison of optimized flowsheet options and the selection of the best option based on economics thus the simulation is needed.

The plant performance has been studied by concerning feed characteristics, the equipment capabilities, influence of specific gravities and size distribution, and the partition curve. In order to calculate the quality of the clean coal and the discard from any unit, a simulator must correctly model the variation of both the cut point and the separation efficiency with particle size.

By concluding chapter 2.2.2.1 all gravity separation units are known to show significant variation of separation performance with particle size.

Decreasing particle size with increasing the cut point and decreasing the efficiency of separation is particularly noticeable at fine particle sizes which is smaller than a few millimeters. This is so-called fine coal separation. The spiral separator deviates from this rule and shows a distinct minimum in the graph of cut point against particle size (16, 17). For this reason, setting the cut point for each cleaning unit should be optimum, and recommended set points can be used in this study.

Previous studies and research have found that many of CPP’s simulation packages are available: LIMN, ModSim and Aspen Plus coal simulation software. LIMN is the most effective simulation tool out of all these programs, therefore, it will be used in this study.

3 Methodology

The problem of this study consists of two parts: to simulate CPP using given washability data and to optimize the yield and quality of coal product after the separation process. The yield is directly proportional to the amount of product from the CPP. Therefore, higher yields will lead to massive amounts of product and the capability to achieve higher sales revenue. Clean coal is traded in accordance with strict quality specifications that will be defined as coal product that ranges within the upper and lower quality specifications of the customer requirements. Another objective can therefore be is to maximize the product yield whilst complying with the customer quality specifications.

The main methodology of this study will be the simulation that is an ideal tool for the examination of alternative cleaning unit operations in cheaper and time-efficient way without any field experimentation. A plant simulation model will then be designed to predict the yield. The plant simulation will be tested for validity by comparing theoretical yield from the given washability data to the predicted yield from the simulation.

This study will examine design limits due to the coal flow circuit, quality requirements, and constraints as well as given washability data. Decision analysis method will be used with a specific focus on simulation, to predict the most viable financial outcome for this study.

3.1 Plant description

A modern CPP flowsheet integrates three or four cleaning circuits that cleans the coarser, intermediate and finer size fraction (12). A simple flowsheet of the plant is shown in Figure 3.

The plant used dense medium separation to clean all of the coal coarser than 1 mm. The feed is screened to separate the coarser particles (60 x 1.2 mm) to be treated by DMC. The material finer than 1.2 mm is then separated by a sieve bend into 1200 x 250 µm that is treated in spiral circuits. The material finer than 38 µm is discarded as slimes while 250 x 38 µm serves as the feed to flotation circuits.

3.1.1 Coarse and intermediate coal cleaning

Coal preparation processes for the coarser and intermediate size fractions, which are lower than 1.2 mm, are designated by a particular amount of highly effective cleaning technologies. Simple gravity separation is not feasible due to the slower settling rates of finer particles as the particle size is reduced to the small. Given the capability and efficiency of existing cleaning unit operations, recent improvements for coarse particle cleaning have supported enhanced capacity and lower operating costs, rather than new innovative technologies that would only marginally improve processing efficiency.

Screening

In this simulation, we used a single deck screen. Screening is not only the most upfront but also it is an efficient method of size classification. As the particle size drops below 0.5 mm, screening becomes very inefficient, as the fine particles cause unnecessary blending (18). For these smaller size fractions, particle classification with hydro-cyclones is used.

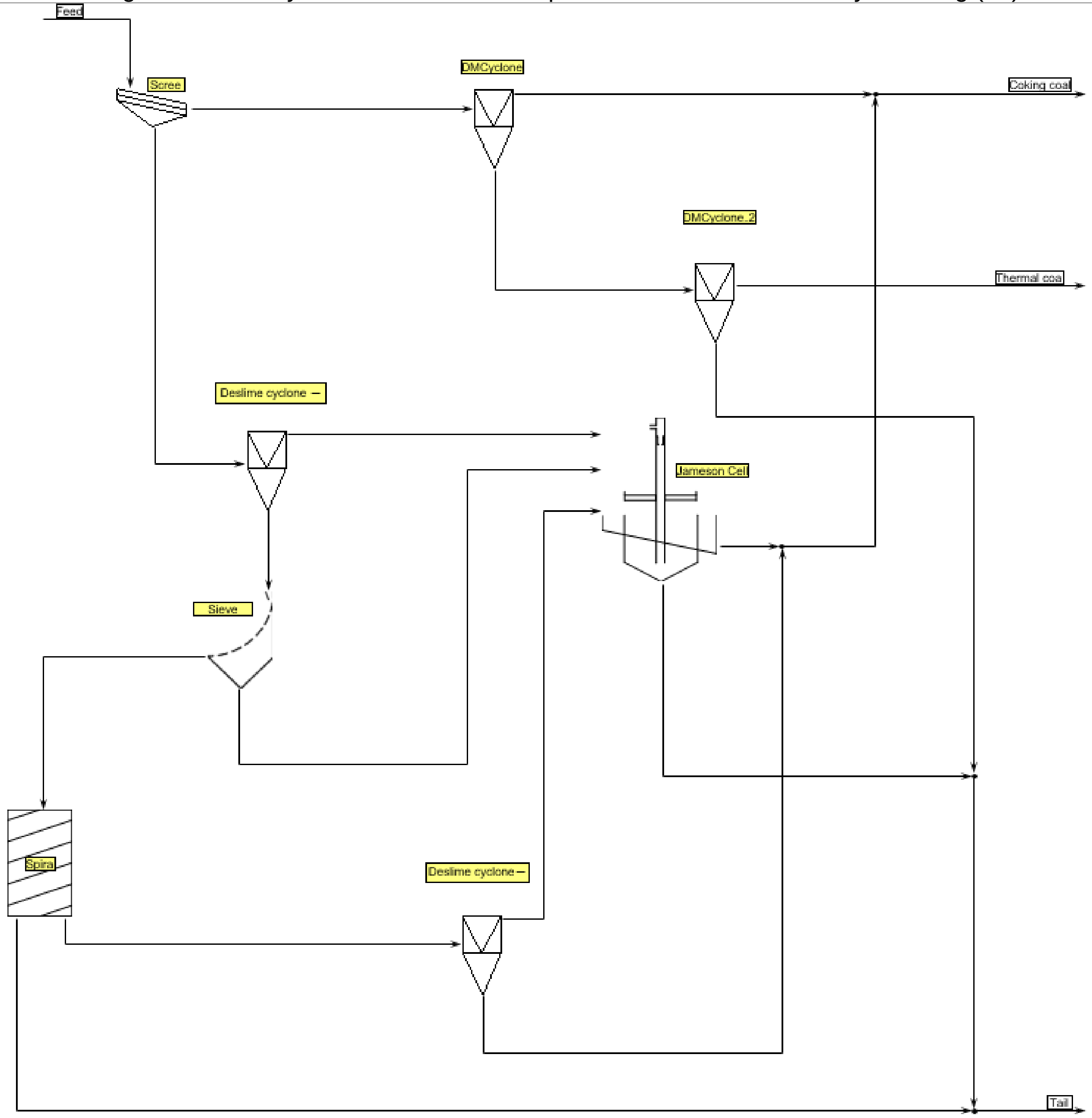


Figure 3. Flowsheet of a modern CPP

The available screen area is the most significant design criterion for coarse coal sizing. This value is a complex function of the feed size distribution, the screen opening size and shape, the amount of water used, the material weight, the open area fraction, and other factors.

DMCs

Coarse and intermediate coal is typically treated in modern coal processing plants using dense medium processes including vessels and cyclones (19). However, DMCs were selected to separate coal in coarse and intermediate size range.

DMCs, also known as heavy medium cyclones, are adaptable separators known to be effective, and suitable for upgrading particles in the 50 – 0.5 mm size range (19). Typical medium SG ranges from 1.4 to 1.6 for metallurgical coal and from 1.6 to 1.7 for thermal coal (18). Even though coarse particles greater than 10 mm can be easily treated in static dense medium vessels, DMCs can also be used to treat even larger size fractions up to 3 inches. Therefore, there is no need to have dense medium vessels, and the vessel circuit can be replaced by the DMCs.

3.1.2 Fine and ultrafine coal cleaning

Fine coal separation is described by several equipment options and numerous flowsheet variations different from coarse coal cleaning. While flotation is broadly used for the fraction below 0.25 mm particles can be processed by one or more water-based gravity separations.

Many operations note that difficulties in processing and handling very fine material (<0.038 mm). At this size range of material often has a high clay content and can cause increased flotation reagent requirements, poor product moisture, and concerns with stickiness (20). Due to these concerns, a “deslime” circuit was involved in the flowsheet. Spirals and Jameson cell are used to separate fine and ultrafine particles in this study.

Spirals

Coal spirals is likely to keep a reliable cut-point across multiple size fractions. They also have few maintenance requirements, low operating costs, and relatively small area requirements.

Basically, spirals use a corkscrew trough to create a thin flowing film. As feed material flows down the spiral, a centrifugal field is generated, forcing lighter material to the edge while retaining heavier material near the core.

Unfortunately, the spiral’s flowing film does not always generate a clear separation point (18).

Jameson cell

It is a high-intensity froth flotation cell which is short from normal conventional column flotation cells. Air compressors are not required to ventilate the suspension of ground ore particles and water in the flotation cell. Rather than most types of the flotation cell, the Jameson cell starts with the feed, and the air to the Jameson cell in a combined stream via one or more cylindrical columns. It produces higher concentrate grades than other types of the flotation cell, and mineral floatation rate is fast. Therefore, it is necessary to select this cell.

3.2 Process variables

3.2.1 Raw feed variables

Influencing factors of the performance of the CPP are a number of raw feed characteristics, for instance, tonnage, particle size distribution, SG distribution, ash-particle size relationship, ash-SG relationship, and hydrophobicity of the coal.

The tonnage and size distribution of the raw feed will determine how much material is treated in each of the three cleaning circuits. Since each circuit performs differently, there will be a direct impact of these variables on the overall plant performance.

The ash-particle relationship will determine the relative partitioning of the feed ash between the three processing circuits.

Most cleaning units use a float-sink principle, in which the lighter coal is separated from the heavier impurities. Hence the specific gravity of the material in each coal stream plays a major role in determining the effectiveness of the separation. The specific gravity distribution and the ash-specific gravity relationship will affect the performances of the dense medium cyclones and spiral circuits, while the hydrophobicity of the coal will influence the performance of the flotation circuits. In the flotation process, the separation is based on differences in surface characteristics instead of specific gravity.

3.2.2 DMC circuit variables

The important fundamental variables are the SG distribution, ash-SG relationship, and the slurry density which will determine the yield and product ash for the dense media circuit.

3.2.3 Spiral circuit variables

The distribution of the SG of the material that goes to the spiral circuit will have a significant effect on the product ash and tails ash. Separation in the spiral circuit is not carried out at a certain SG of separation, rather the relative split between the product and reject streams is managed to achieve overall clean coal ash levels.

3.2.4 Flotation circuit variables

Feed characteristics and operation variables will dictate the performance of the flotation circuit. Related feed characteristics are the ash content and the hydrophobicity of the coal which, in order, may be associated with the fluidity, free-swelling index, and rank of the coal. Principal operating variables consist of the cell retention time, the frothier type and dosage, collector dosage, and promoter dosage.

3.3 Modelling

This chapter presents coal processing circuits that could be used to achieve various outcome involved to different grade products.

3.3.1 Input data into Limn

The primary input data is sizing data. Table 2 shows the nominal wet screen analysis after wet tumbling. Plants are always designed on wet sizing data, often called “plant feed sizing” to allow for particle breakdown in handling and wet processing.

Float sink analysis was performed on only 5 size fractions. In order to maintain the 10 size fractions shown in **Error! Reference source not found.**, the float sink fractions will be split into sub-fractions. Each sub-fraction will have the same washability distribution as its parent fraction.

Table 2. Sizing data

Fraction	**Mass**	**Cumulative mass /Passing/**
mm	%	%
- 50 + 32	16.71	100.0
- 32 + 25	5.14	83.29
- 25 + 19	5.07	78.15
- 19 + 9	16.49	73.08
- 9 + 6	6.18	56.59
-6 + 2	18.28	50.41
- 2 + 1	8.32	32.13
- 1 + 0.25	9.93	23.81
-0.25 + 0.074	8.11	13.88
-0.074	5.77	5.77
	100.0	

Float-sink analyses and ash contents on a size-by-size basis are calculated and prepared based on the mass recovery and the ash content of each flowsheet stream and product. Float-sink data and additional data for sulfur is inserted into the program.

3.4 Data analysis

Washability data

The CPP obtain the initial feed data and size-by-size washability data. A graphical form is needed to expand the use of the information. The five graphs are commonly produced and referred to as the washability curves of the coal. A washability table (Table 6) indicates the relationship between the medium density and the cumulative particles that float, as the wash density increases incrementally.

The data from **Error! Reference source not found.**6 are plotted the following figures to show the ease of washability and the partition curves. The cumulative float curve, which is shown in Figure 4, shows the relationship between the yield of clean coal and the ash of the coal. Consequently, if the ash is known then the yield can be found from the graph.

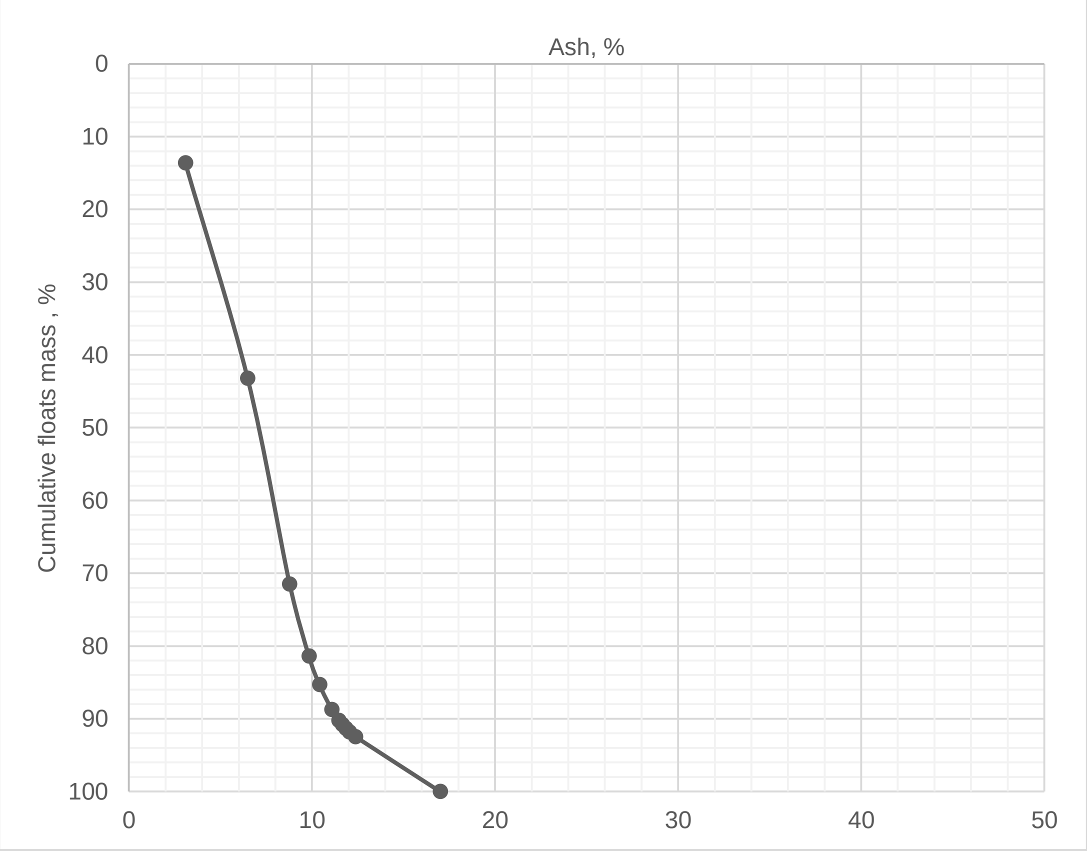


Figure 4. The Cumulative floats curve

The cumulative sinks curve, Figure 55, gives the relationship between the yield or percentage of sinks, and the ash content of the sinks.

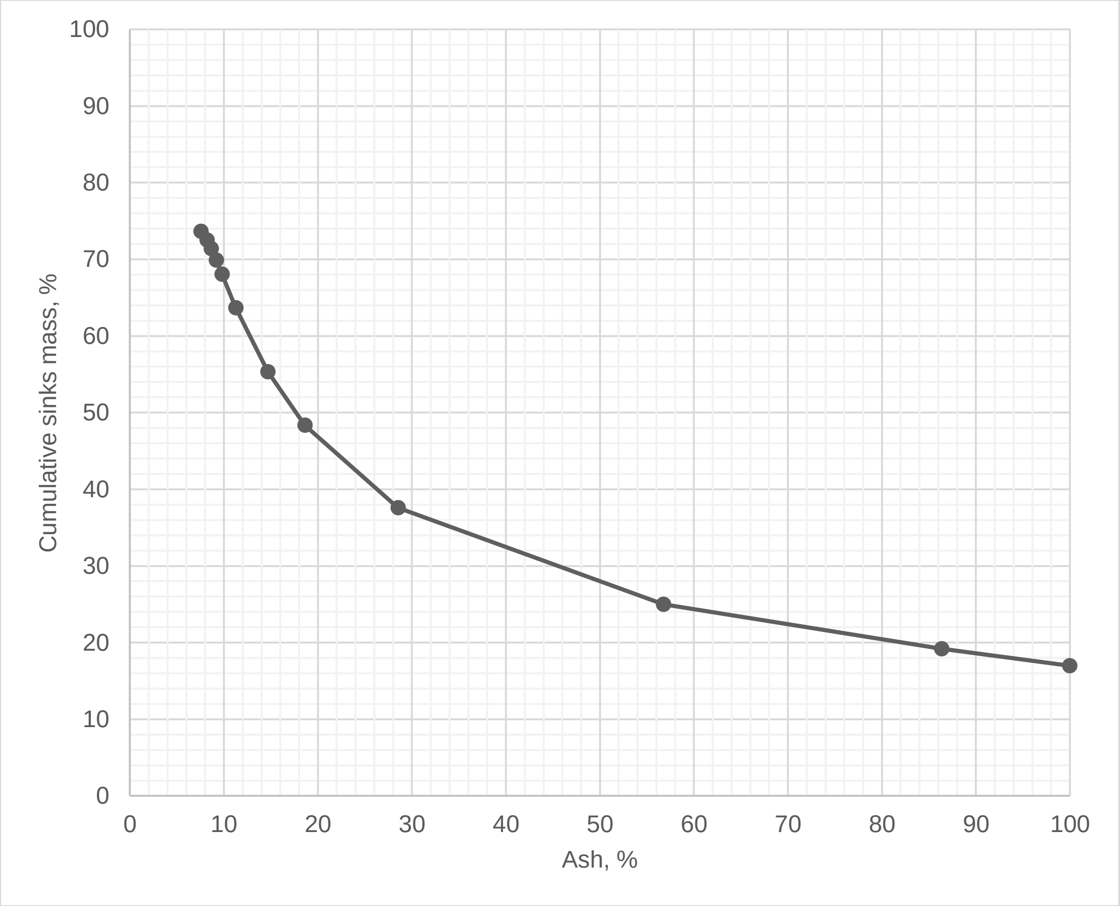


Figure 5. The Cumulative Sinks Curve

The relative density curve shows the relationship between the relative density of the separation and the theoretical yield of clean coal (see Figure 6).

The instantaneous ash curve, which is shown in Figure 77, gives the relationship between the yields of floats and the ash of the particle which has the highest ash in the floats product and/or the lowest ash of any particle contained in the sinks product. More importantly, the curve represents a rate of change of ash with the yield of float coal. The shape of the curve will depend on the amount of middling present. The curve is nearly horizontal in the middle, therefore, the amount of middling is small.

According to Figure 8, vertical section of small distance between the instantaneous ash curve and the cumulative floats curve shows that for large changes in yield the change in ash is small. Hence, the shape of the instantaneous ash curve gives an indication of how easy or how difficult the coal is to wash.

A low quantity of middling makes an easy separation in the feed, and the cut point may not be that critical. All the curves described shown in **Error! Reference source not found.**4,Figure 55,**Error! Reference source not found.**6 and Figure 77 are related and termed as washability curves.

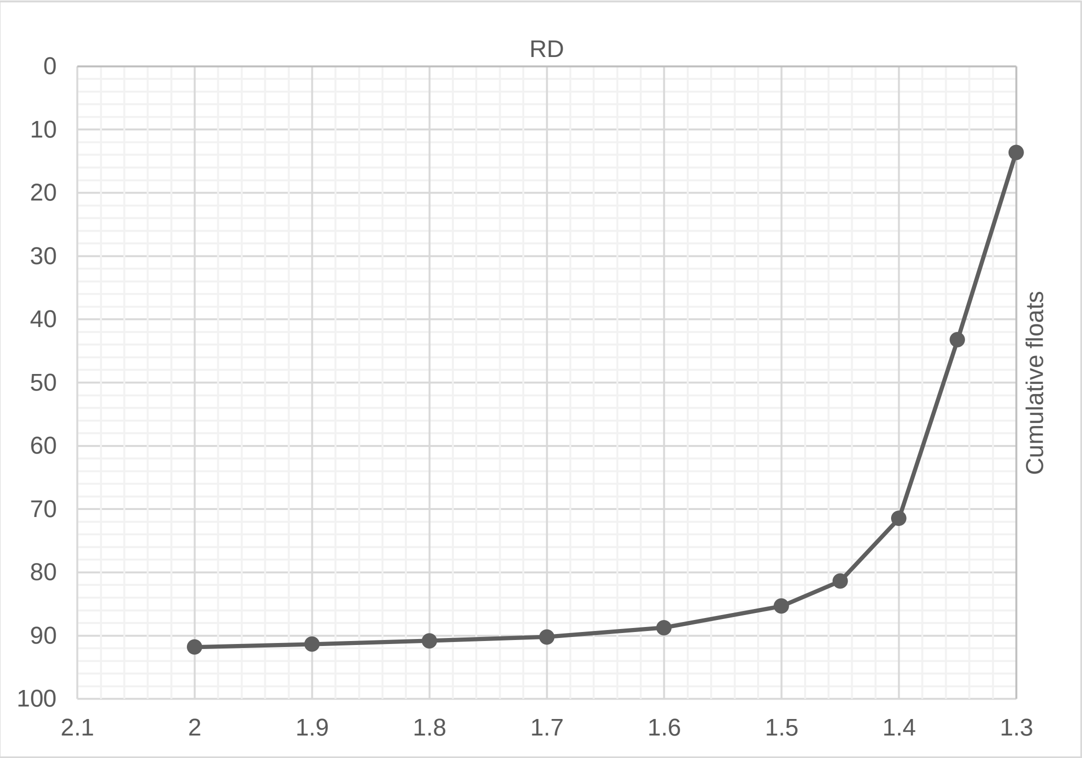
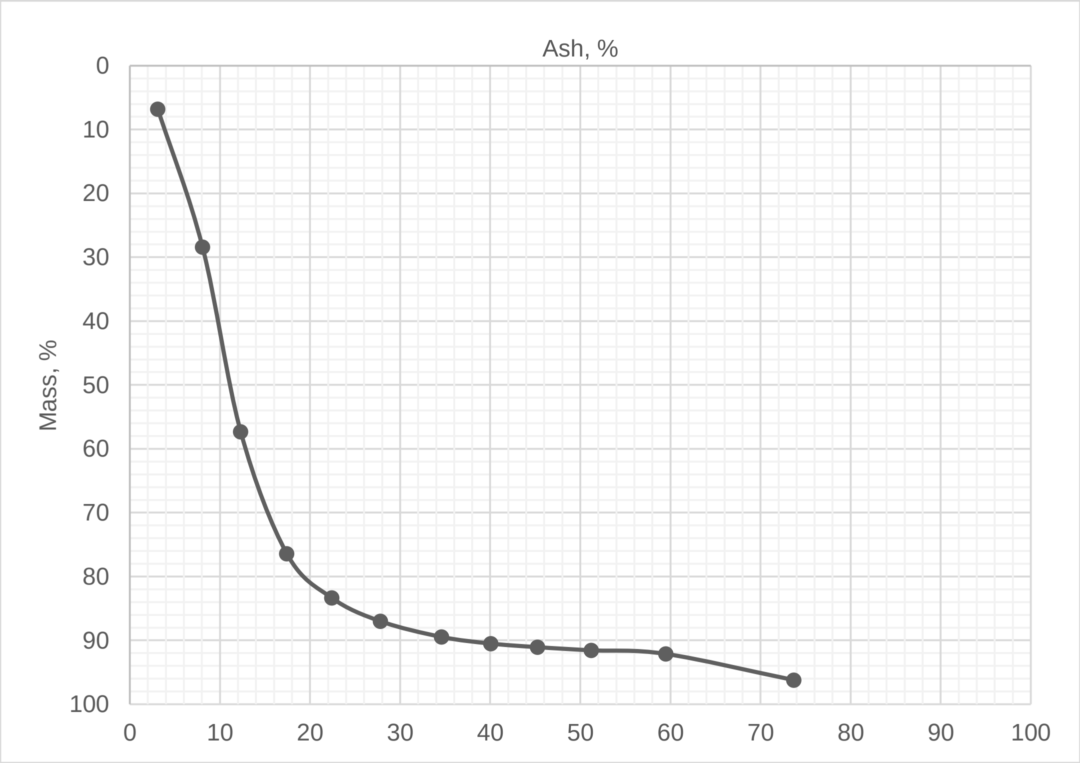


Figure 6. The Relative Density curve



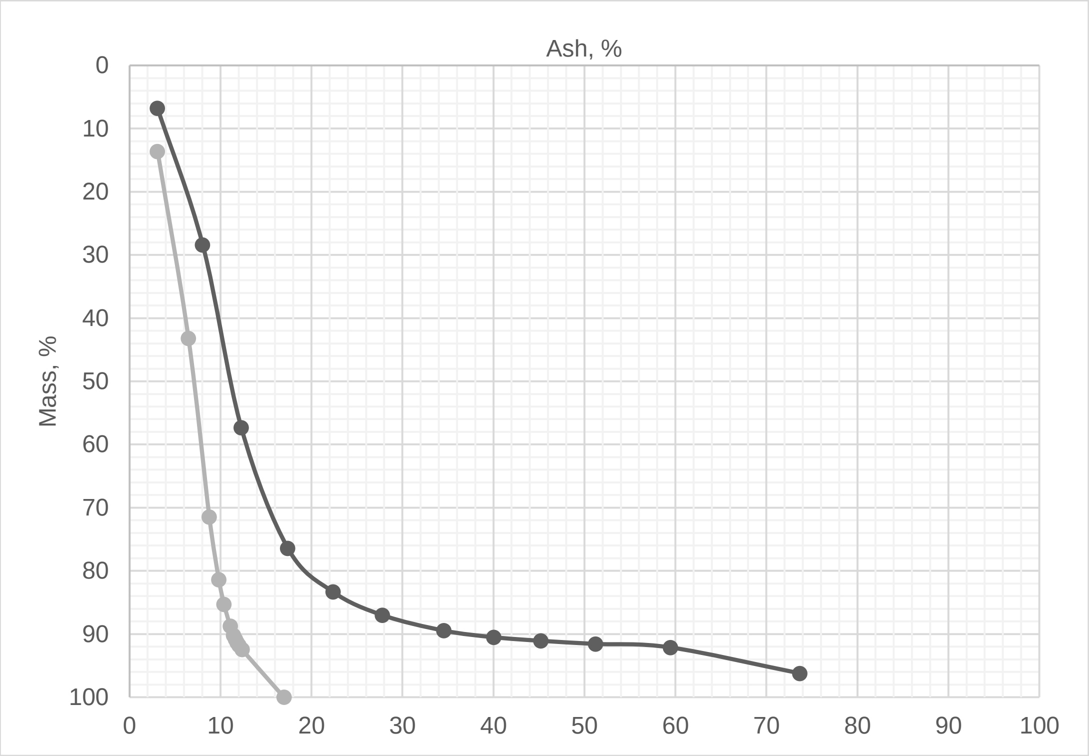


Figure 8. The Instantaneous Ash Curve (black-dotted) and the Cumulative Floats Curve (gray-dotted)

Ease of washing

The very first step when regarding the processing of any coal is to find out how easy or difficult it will be to treat it. One of the most useful characteristics of the washability curves is that a qualitative assessment of the ease of washing can be obtained by simple visual investigation and a quick reading of the curves.

Two of the curves are particularly useful:

- the instantaneous ash curve, and
- the ±0.1 density curve.

As shown in Figure 7, the coal presents a sharp inflexion indicating a natural point of separating coal from other material. This shows that it is easy coal to treat, all the coal will separate cleanly leaving the impurities in the discard.

The ±0.1 RD curve can be used to illustrate the ease of separation numerically on the scale. Based on the ±0.1 RD distribution read from its curve, a scale of “ease of separation” is often quoted as listed in Table 33.

Figure 7. The Instantaneous Ash Curve

Table 3. Conventional Scale for "Ease of separation"

± 0.1 RD %	“Ease of separation”
< 7	Simple
7 – 19	Moderately difficult
10 – 15	Difficult
15 – 20	Very difficult
20 – 25	Exceedingly difficult
> 25	Formidable

Therefore, it is necessary to analyze the data again to determine difficulty level of separation. The analyzed data are shown in Table 44. From that, it can be seen as simple separation.

Table 4. ±0.1RD curve data

Fractions	Mass	Mass
Units	(%)	±0.1RD %
F1.30	13.62	
S1.30-F1.35	29.60	
S1.35-F1.40	28.25	71.70
S1.40-F1.45	9.91	
S1.45-F1.50	3.93	17.26
S1.50-F1.60	3.42	8.82
S1.60-F1.70	1.47	5.50
S1.70-F1.80	0.60	2.61
S1.80-F1.90	0.53	1.59
S1.90-F2.00	0.46	
S2.00-F2.20	0.65	

Partition data

In order to estimate the performance of the selected equipment, it is necessary to have access to partition data for the particular units. Partition data (see) depends on the cut point selected for the separation

3.5 Simulation

In addition to coal quality and yield, a plant simulation was created to evaluate the various feed scenarios where washing is required. Flowsheet simulation is commonly used during process design, optimization and flexibility or sensitivity analysis (21). Flowsheet simulation indicates the numerical solution of material balances and the determination of the intensive properties for varying process structures and substances on the basis of coupled mathematical models for the different process steps (21). The aim of the plant's flowsheet simulation is to obtain accurate yield and quality predictions as it includes data regarding equipment capacity, equipment efficiency, flow rates and equipment design capacities. Prior to explaining the results achieved for the various feed scenarios, the plant simulation and the logic of the simulation will be explained.

Process modelling was completed using coal preparation models derived from actual plant operation data, and the LIMN "The Flowsheet Processor" software which was developed by D.Wiseman in 1994 and is a Microsoft Excel based software package that can be used for mineral processing circuit modelling applications.

The circuits were modelled according to their feed size classification:

- Coarse size fraction: - 150 + 12 mm
- Medium size fraction: - 12 + 0.5 mm
- Fine size fraction: - 0.5 + 0.15 mm
- Ultra-fine size fraction: -0.15 mm

Most coal plants run under conditions of varying feed scenarios or are asked to produce qualities different from design specifications (6). This can cause overloaded conditions which is also called "bottlenecks" in the plant, either depending on the way the plant is operated or as the feed scenario changes.

3.5.1 Description of the simulator

Limn: The Flowsheet Processor is used to simulate the coal plant in detail, in order to determine the yield of specific feed type. The yield was determined by adding the total product tons generated and dividing it by a plant feed rate of 855 tons per hour, based on the plant design per module. The input data used for Limn was obtained from the company which has partnership with our university. The predicted feed washability and feed particle size distribution served as inputs into the Limn model.

Before the plant can be optimized, it is necessary to investigate the performance of each individual washing unit under conditions that is in the flowsheet. The simulator can therefore be used to examine the range of performance of each washing unit in the plant.

The Limn installation allows the user to:

- Draw a flowsheet
- Connect each process unit with streams
- Describe the streams conditions such as composition, size, temperature, etc., as required
- Mathematically describe each process unit and its impact on the streams, to produce output streams
- Iteratively solve a complex flowsheet.

Limn has been applied in a different range of industries and processes such as, minerals, coal, hydrometallurgy, pyrometallurgy, pigment, cement, and even diamonds. Depending on which industry, different optimization of data structure for the respective application.

For coal plants, the density-based two dimensional data structure with specific gravity and size should be used – so called ‘The coal-specific model’. Additionally, some components, such as ash, sulfur, CV, iron etc. can be tracked as assays. In this simulation, ash, sulfur and CV were traced as assays.

4 Results and Discussions

In order to estimate the performance of the selected equipment, it is necessary to investigate the performance of each of the individual cleaning units under conditions that each of experiences in the flowsheet. This is the first task for the simulator which can be used to investigate the range of performance of each cleaning unit in the plant. The performance of each cleaning unit in the flowsheet was simulated over a range of target cut points. The results are summarized in Figure 9. The figure shows the cumulative yield against the cumulative ash for DMCs with the theoretical yields calculated from the washability data of the feed material to each unit.

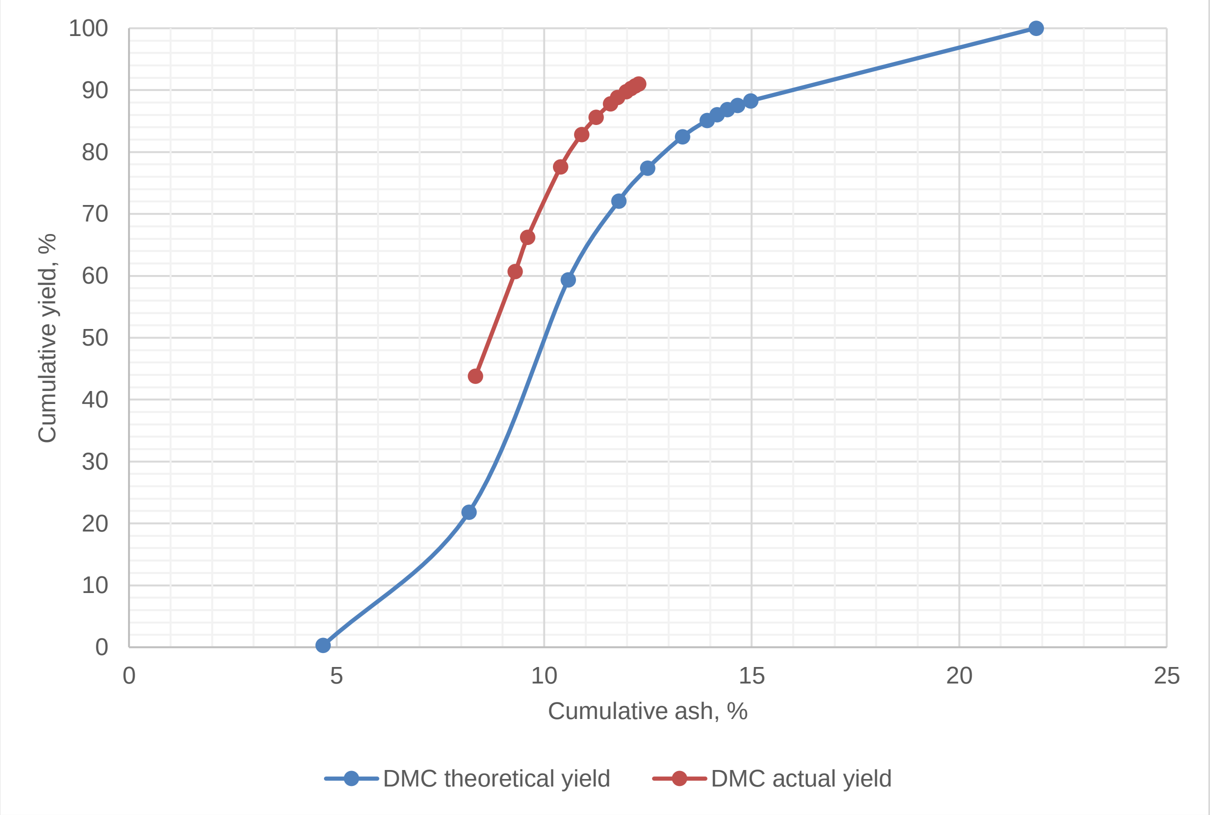


Figure 9. Simulated performance curve for DMC

In the present case, such data are provided for three options on the different fractions for an estimated cut point of 1.39 RD. We can input required data which is needed to calculate cut point density and the yield, ash, sulfur content and CSN are available to estimate easily by using Limn program. In other words, the yield, ash, sulfur content and CSN are calculated respectively as cut point density is changed.

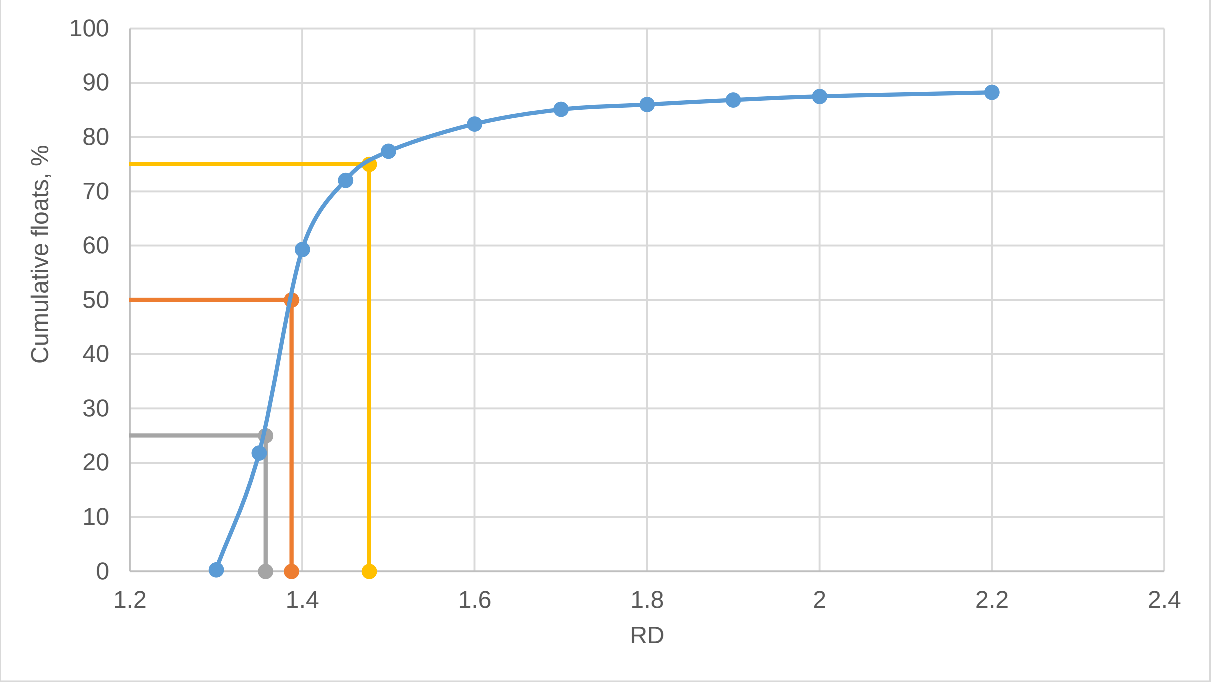


Figure 10. The Relative Density Curve of DMC with d25, d50, and d75

Before the simulation, the cut point density was estimated around 1.39 which is shown in Figure 10 theoretically.

By using Scenario part in Limn, the overall yield, ash, sulfur and CSN were calculated (Table 5). An important characteristic is already noted from Figure 10, which is that increasing the density of separation would add relatively little to yield but the ash of the extra mass will be high.

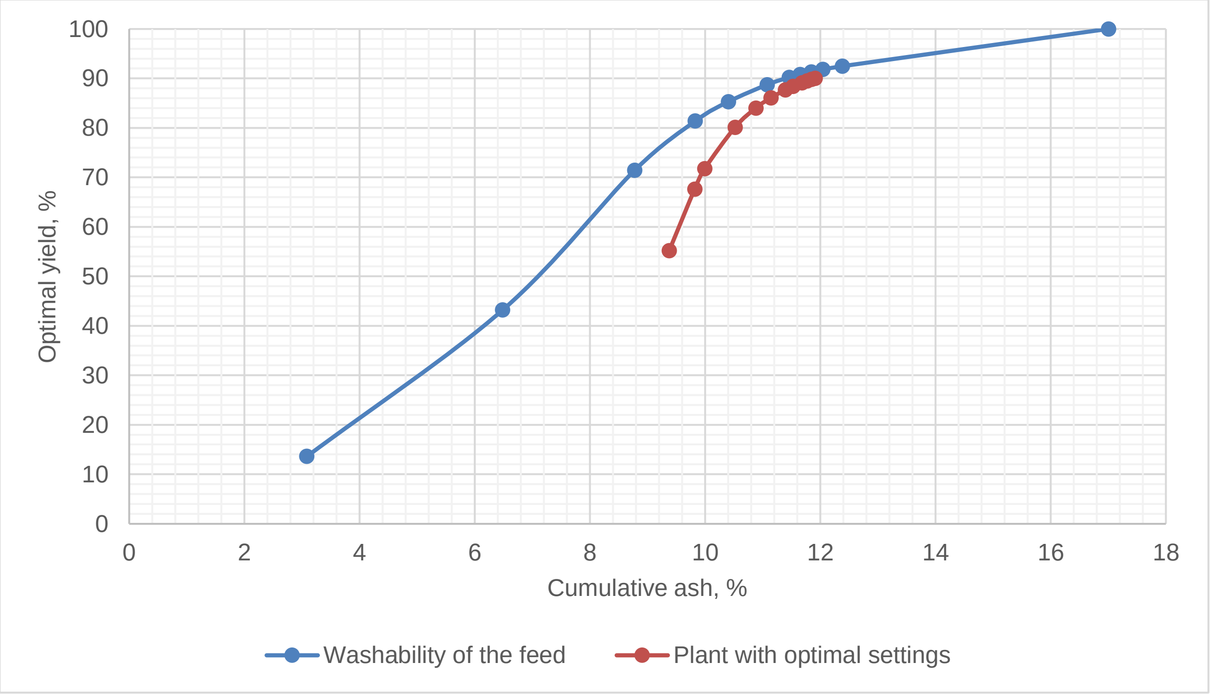


Figure 11. Optimal performance curve for the plant compared to the washability of the feed

As a result, it was recommended that simulations should be based on the following set point: DMC 1.39.

The performance of the simulated plant with the optimum cut points is shown in Figure 11. It is immediately clear that this set point would lead to grossly inefficient operation and should not seriously be considered for any plant that has units operating as described by the models used here. Moreover, the washability of the feed represents the extreme limit of good plant performance and will be achieved only if cleaning units in the flowsheet is operated with perfectly clean separations and the optimal cut point is used.

In addition to the selection of optimal cut points for the DMCs, simulation is an ideal tool for the investigation of alternative cleaning unit operations without the need for expensive and time-consuming plant or field experimentation. In the flowsheet, it consists of not only DMCs, but also spiral for fine cleaning and Jameson cell for ultra-fine cleaning.

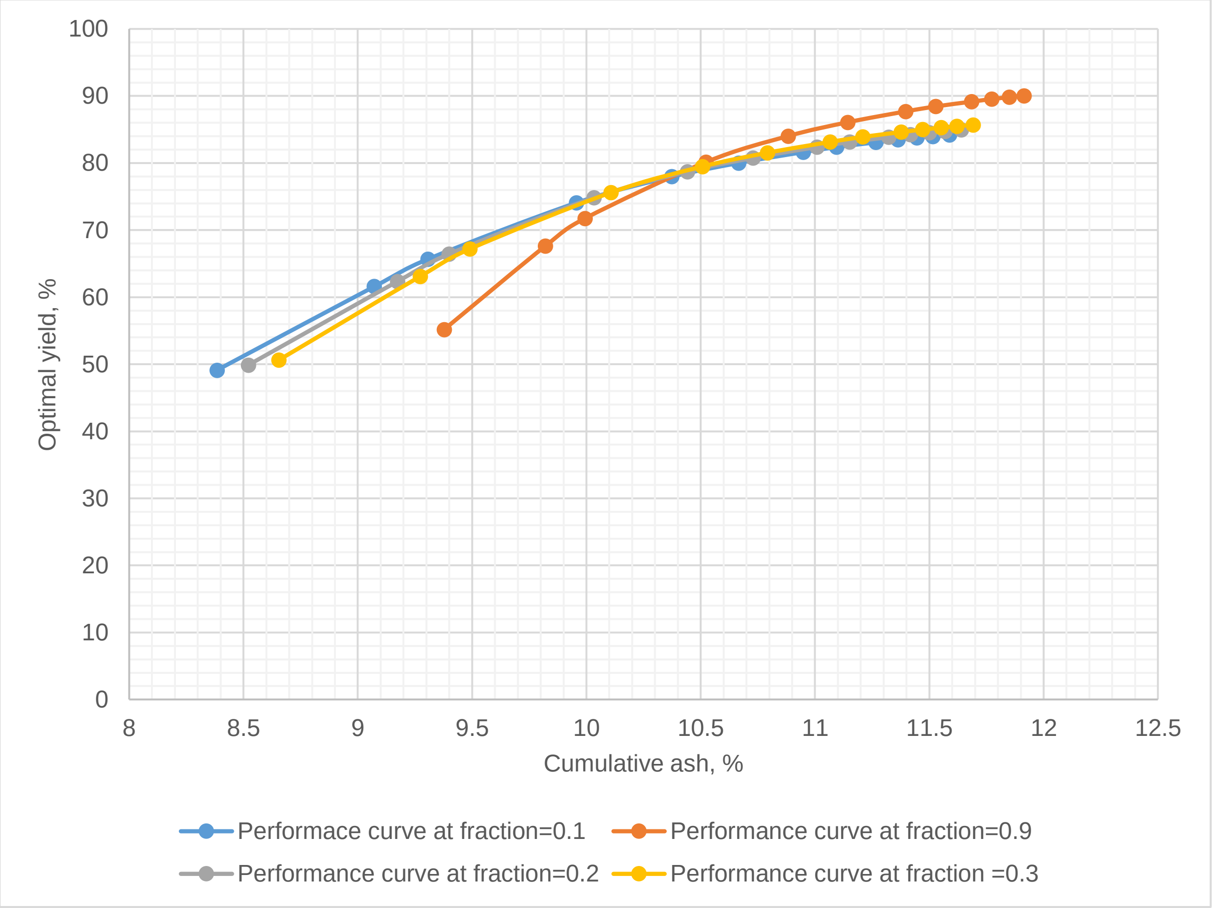


Figure 12. Performance curves at different concentration fraction of Jameson cell

The deviation of the curve from the “perfect separation” curve gives a measure of the efficiency of the cleaning unit. As particle size decreases, the deviation is much higher, and separation becomes less efficient. In Figure 13, DMCs efficiency can be predicted, because it is obvious that DMC works effectively above 1 mm, and the deviation is low. The performance characteristics of a spiral concentrator as described by partition curves are given in Figure 14.

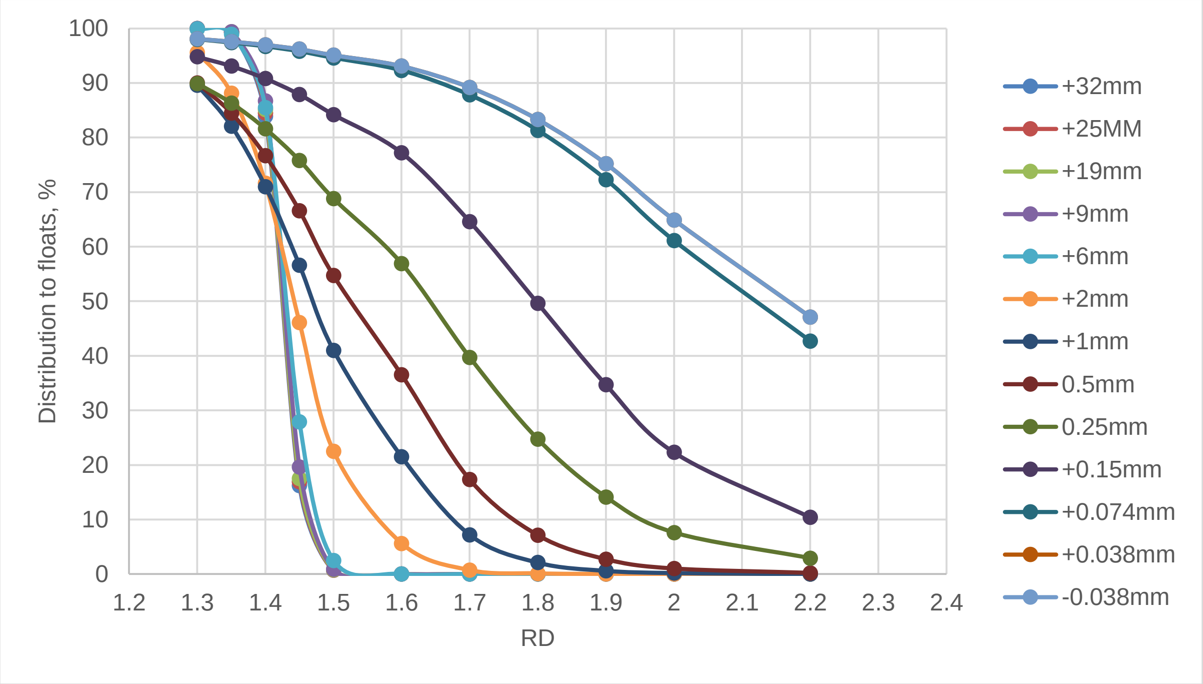


Figure 13. Partition curves of DMC at different sizes

It has been observed also that the variation of D_{50} with particle size is small and is approximately constant over the particle size range 1.0 to 0.125 mm. This suggests that for optimum efficiency, the lower particle size limit for spiral feed should be in the range of 0.1-0.2

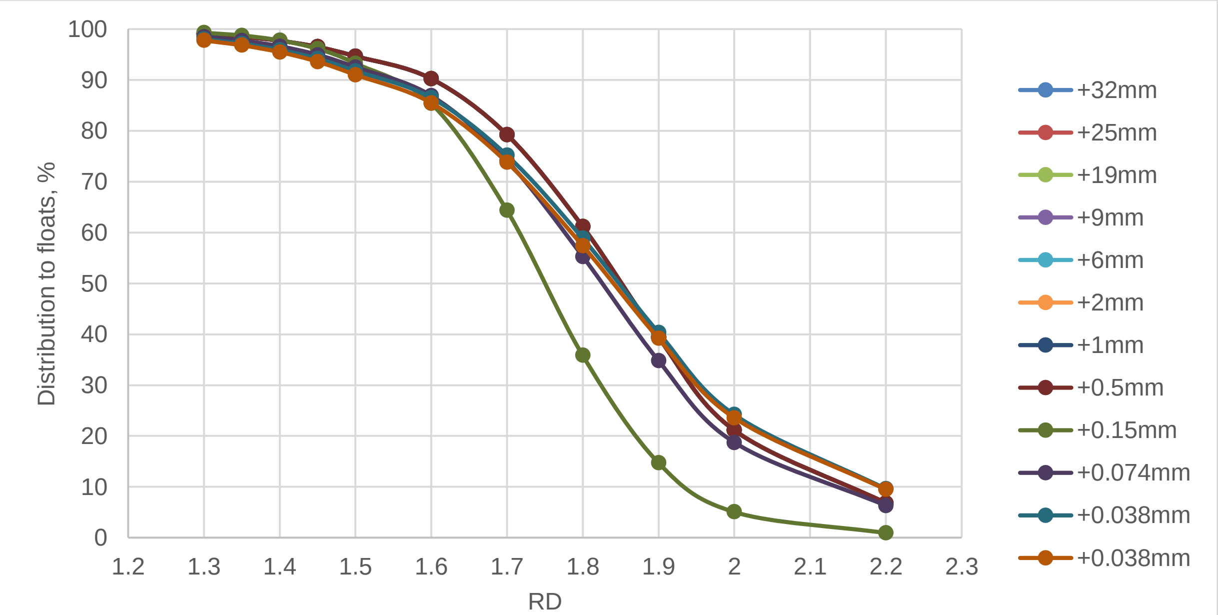


Figure 14. Partition curves of spiral at different sizes

mm, with finer particles being treated separately. Compared to spiral efficiency with DMC, spiral is more efficient for finer particle, and it can be seen from Figure 14.

The optimal combination of DMCs and Jameson cell control setting were obtained and constructed in Figure 12 using optimization procedure that was used for the flowsheet.

Table 5. Optimal setting of cut point density for the DMCs in the plant and the resulting plant performance

Cut point density	Yield, %	Ash, %	CSN
1.39	67.65	9.82	6 1/2
1.40	71.74	9.99	6 3/7
1.45	80.13	10.52	6 1/9
1.50	84.02	10.88	6
1.54	86.07	11.14	5 6/7
1.59	87.69	11.40	5 7/9
1.63	88.43	11.53	5 3/4
1.67	89.15	11.69	5 5/7
1.72	89.53	11.77	5 2/3
1.76	89.82	11.85	5 2/3
1.80	90.03	11.91	5 2/3

The simple solution to an important practical operating problem given here immediately raises the question of reliability of the solution. Can the results obtained here be applied to a particular operating coal preparation plant and optimal performance realized? The answer must negative since that would expect too much of the models used in the simulator. The models would first have to be calibrated in contradiction of operating data that is known to be relevant to the specific units as they operate in the plant.

The method developed here can be used on a continuing basis with optimal settings determined as frequently as required to allow the plant to perform optimally in the face of varying characteristics of the plant feed.

Figure 15 and Figure 16 show the comparison of the simulated yield and ash values with the theoretical yield and ash values from float-sink data of the plant, respectively. As can be seen from Figure 15 and Figure 16, the results were in a good agreement with each other. R^2 values of both correlations are no less than 0.99 indicating that simulation result represents the float-sink data well. Thus, Limn can be accepted as an acceptable modelling tool to predict product yields.

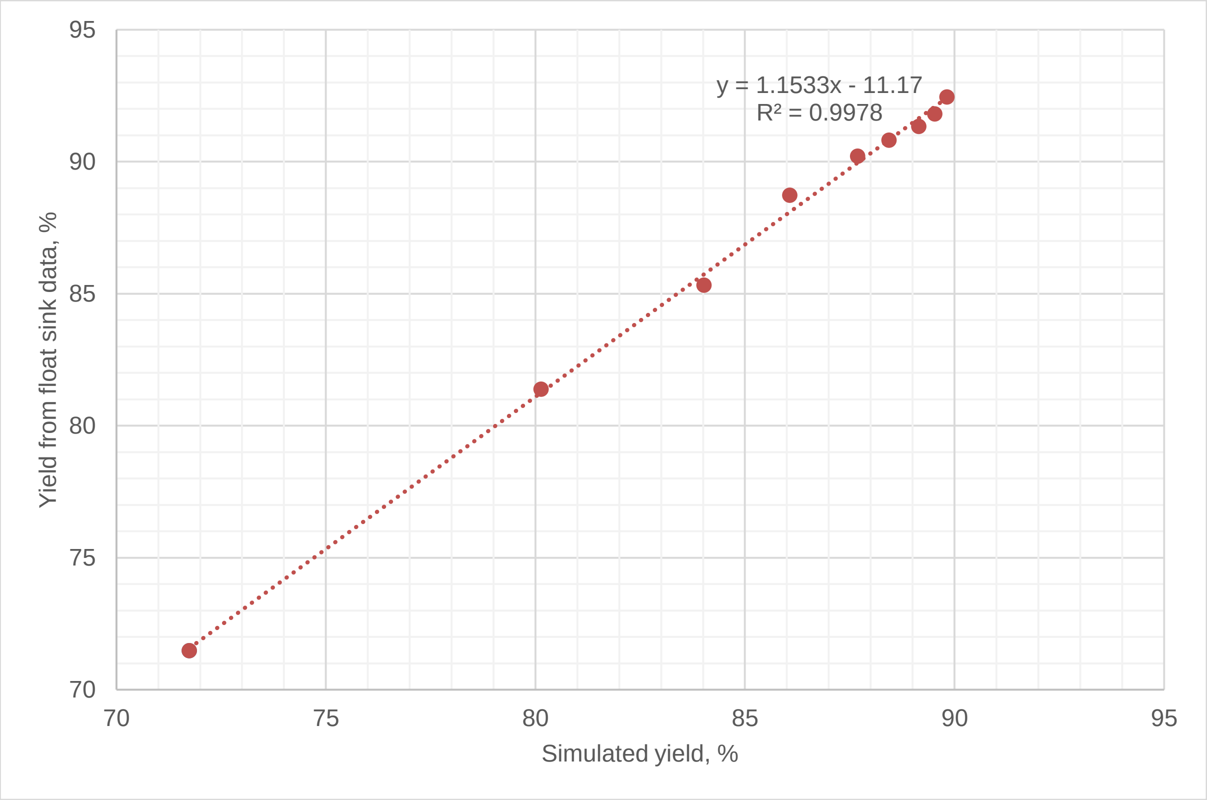


Figure 15. Comparison of simulated yield and theoretical yield

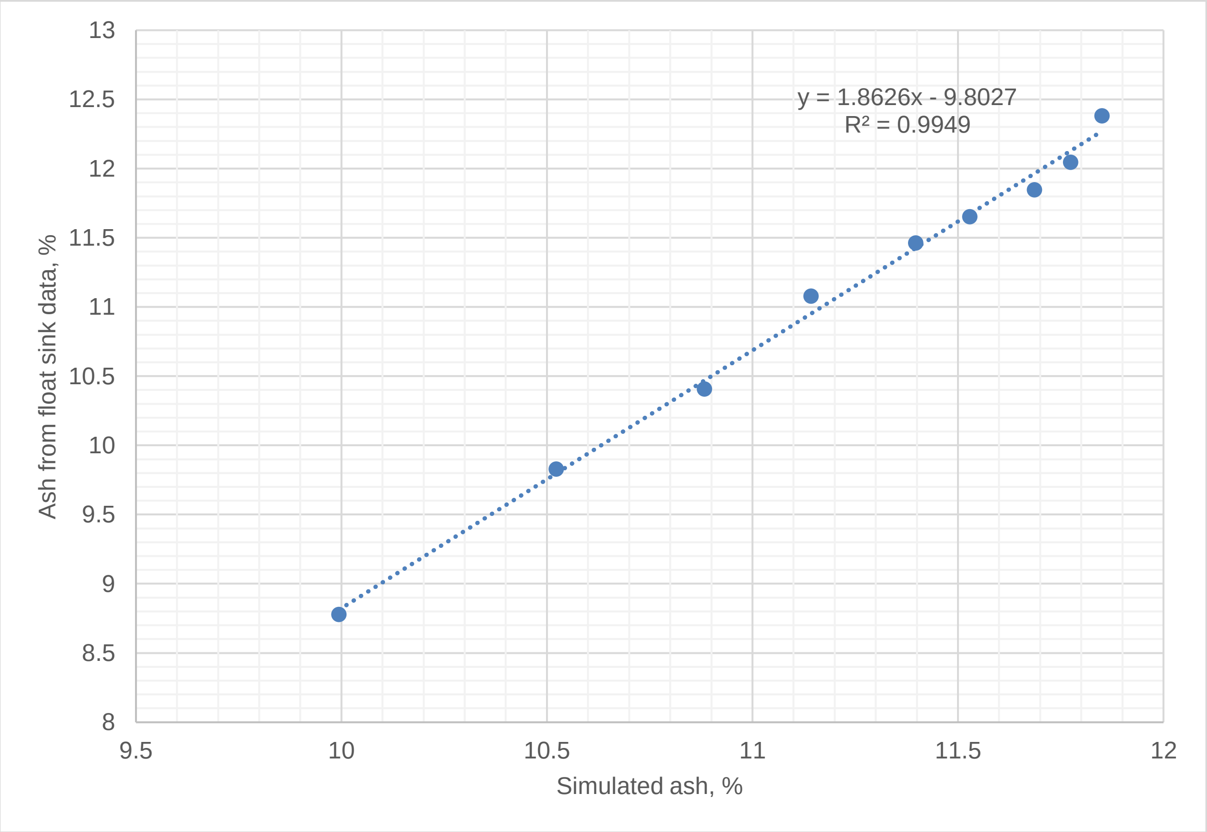


Figure 16. Comparison of simulated ash and theoretical ash

One of the biggest step before starting the simulation, the models would first have to be calibrates against operating data that is already known to be relevant to the specific units as they operate in the plant. This would not be an enormous task and is routine for the application of simulation techniques in mineral processing plant. However, the simulator could not be calibrated due to lack of availability of known operating data in this study.

The graphical method that is proposed here for the selection of optimal operating cut points for the individual units can be based entirely on experimental data.

5 Conclusions and Recommendations

In order to benefit the design and management of coal preparation plants, several simulation and yield optimization programs have been developed. This concept dictates that all plant circuits be operated at the same quality to maximize the yield of clean coal product. For efficient processes such DMCs, this constraint can be achieved for all practical purposes by operating all parallel circuits at the same effective RD cut point. The computer model was validated by testing the model results against theoretical plant experience. The washability data of the plant feed was used as input to the model and the value of the observed ash, sulfur and CSN used as quality constraint. The reason why CSN was chosen is that CSN can express the coal quality especially, the coking coal very well.

In general, the simulated results were similar to the theoretical results. It is concluded then, that the model is valid and useful as a tool for predicting plant results for separation above 1.39 SG.

Limn operates within a spreadsheet, it has the major advantage of allowing the user total freedom to create and modify their own models for each unit. Moreover, simulation is necessary to plan new projects or the modification of existing operations. The simulator is easy to use and could readily be expanded to include a wide range of feed materials.

To calculate the predicted yield from a dense medium separation, it is necessary to apply distribution factors from a distribution curve to the raw coal washability data. This presents a problem from two aspects:

- The shape of the curve varies with the SG of the separation;
- The representation of the curve in computer form so that interpolation between known points is possible.

The plant simulation can be set up to be fully balanced in terms of material, water, and magnetite. Even though the simulator provides useful data, these data should be analysed and summarized by graphical approach and linear approach.

The future prospect of the study lies in online analysis systems which would make it possible to interface the simulator with control systems to provide more advanced applications and defining a cost function that is suitable enough to consider all the possible quality constraints. These applications could include the real-time gathering of process data and subsequent updating of the regressions used to model the process. However, analyzers cannot be used to accurately determine important data such as particle size distributions and real-time washability. Therefore, improving automation, control, and sensor technologies is a key challenge for the industry to overcome.

The main objective of further research can be to reduce the energy consumption without reducing the recovery or the grade of the final product.

Finally, Limn can be used for other industrial processes, therefore, it is available to know and to analyze the performance of the simulation program.

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Appendices

Table 6. Washability table - Extended form

1		2	3	4	5	6	7	8	9	10	11	12
Fractions	**Float SG**	**Mass,**	**Ash, d**	**Ash**	**Mass,**	**Ash**	**Ash, d**	**Mass**	**Ash**	**Ash**	**Mass**	**Mass**
		(%)	**(%)**	**units**	**(%)**	**units**	**(%)**	**(%)**	**units**	**(%)**	**(%)**	**±0.1RD %**
F1.30	1.3	13.62	3.08	42.01	13.62	42.01	3.08	100.00	1700.63	17.01	6.81	
S1.30-F1.35	1.35	29.60	8.05	238.30	43.22	280.31	6.49	86.38	1658.62	19.20	28.42	
S1.35-F1.40	1.4	28.25	12.29	347.19	71.47	627.50	8.78	56.78	1420.32	25.01	57.35	71.70
S1.40-F1.45	1.45	9.91	17.41	172.52	81.38	800.02	9.83	28.53	1073.13	37.62	76.43	
S1.45-F1.50	1.5	3.93	22.39	88.04	85.32	888.05	10.41	18.62	900.61	48.38	83.35	17.26
S1.50-F1.60	1.6	3.42	27.82	95.06	88.73	983.11	11.08	14.68	812.57	55.34	87.03	8.82
S1.60-F1.70	1.7	1.47	34.57	50.94	90.21	1034.06	11.46	11.27	717.51	63.69	89.47	5.50
S1.70-F1.80	1.8	0.60	40.04	24.21	90.81	1058.26	11.65	9.79	666.57	68.07	90.51	2.61
S1.80-F1.90	1.9	0.53	45.23	23.84	91.34	1082.10	11.85	9.19	642.36	69.91	91.08	1.59
S1.90-F2.00	2	0.46	51.22	23.73	91.80	1105.83	12.05	8.66	618.52	71.42	91.57	
S2.00-F2.00	2.2	0.65	59.48	38.91	92.46	1144.74	12.38	8.20	594.79	72.56	92.13	
S2.00-F2.20	S2.20	7.54	73.69	555.89	100.00	1700.63	17.01	7.54	555.89	73.69	96.23	
Total		100.00										

Table 7. Washability table - Extended form at 50-19mm size

1		2	3	4	5	6	7	8	9	10	11	12
Fractions	**Float SG**	**Mass, (%)**	**Ash, d (%)**	**Ash units**	**Mass, (%)**	**Ash units**	**Ash, d (%)**	**Mass (%)**	**Ash units**	**Ash (%)**	**Mass (%)**	**Mass ±0.1RD %**
F1.30	1.3	0.30	4.67	1.41	4.67	100.00	21.85	0.15	2185.21	21.85	0.15	
S1.30-F1.35	1.35	21.53	8.23	177.28	8.18	99.70	21.90	11.07	2183.79	21.90	11.07	
S1.35-F1.40	1.4	37.50	11.97	448.88	10.58	78.17	25.67	40.58	2006.51	25.67	40.58	77.09
S1.40-F1.45	1.45	12.74	17.47	222.52	11.79	40.67	38.30	65.70	1557.63	38.30	65.70	
S1.45-F1.50	1.5	5.32	21.96	116.84	12.49	27.93	47.81	74.73	1335.11	47.81	74.73	13.04
S1.50-F1.60	1.6	5.06	26.11	132.07	13.33	22.61	53.89	79.92	1218.27	53.89	79.92	8.63
S1.60-F1.70	1.7	2.66	32.44	86.34	13.93	17.55	61.90	83.78	1086.19	61.90	83.78	4.41
S1.70-F1.80	1.8	0.91	36.06	32.85	14.16	14.89	67.17	85.57	999.86	67.17	85.57	2.41
S1.80-F1.90	1.9	0.84	40.47	33.85	14.41	13.98	69.20	86.44	967.01	69.20	86.44	
S1.90-F2.00	2	0.66	46.09	30.56	14.65	13.14	7102	87.19	933.16	71.02	87.19	
S2.00-F2.00	2.2	0.74	53.04	39.20	14.98	12.48	72.35	87.89	902.59	72.35	87.89	
S2.00-F2.20	S2.20	11.74	73.57	863.39	21.85	11.74	73.57	94.13	863.39	73.57	94.13	
Total		100.00										

Table 8. Washability table - Extended form at 19-9mm size

1		2	3	4	5	6	7	8	9	10	11	12
Fractions	**Float SG**	**Mass,**	**Ash, d**	**Ash**	**Mass,**	**Ash**	**Ash, d**	**Mass**	**Ash**	**Ash**	**Mass**	**Mass**
		(%)	**(%)**	**units**	**(%)**	**units**	**(%)**	**(%)**	**units**	**(%)**	**(%)**	**±0.1RD %**
F1.30	1.3	2.35	4.70	11.04	2.35	11.04	4.70	100.00	1616.91	16.17	1.17	
S1.30-F1.35	1.35	40.77	8.32	339.30	43.12	350.34	8.12	97.65	1605.87	16.44	22.73	
S1.35-F1.40	1.4	31.85	13.02	414.58	74.97	764.92	10.20	56.88	1266.57	22.27	59.04	86.92
S1.40-F1.45	1.45	10.25	17.95	183.92	85.21	948.83	11.13	25.03	851.99	34.04	80.09	
S1.45-F1.50	1.5	4.05	23.09	93.55	89.27	1042.38	11.68	14.79	668.08	45.19	87.24	
S1.50-F1.60	1.6	3.35	29.44	98.78	92.62	1141.17	12.32	10.73	574.53	53.52	90.94	8.34
S1.60-F1.70	1.7	0.93	37.39	34.81	93.55	1175.98	12.57	7.38	475.74	64.47	93.09	4.65
S1.70-F1.80	1.8	0.36	40.91	14.91	93.92	1190.88	12.68	6.45	440.93	68.38	93.73	1.66
S1.80-F1.90	1.9	0.37	47.47	17.42	94.28	1208.30	12.82	6.08	426.03	70.03	94.10	1.05
S1.90-F2.00	2	0.32	51.01	16.30	94.60	1224.60	12.94	5.72	408.61	71.48	94.44	
S2.00-F2.00	2.2	0.44	57.31	25.18	95.04	1249.78	13.15	5.40	392.31	72.69	94.82	
S2.00-F2.20	S2.20	4.96	74.05	367.13	100.00	1616.91	16.17	4.96	367.13	74.05	97.52	
Total		100.00										

Table 9. Washability table - Extended form at 9-2mm size

1		2	3	4	5	6	7	8	9	10	11	12
Fractions	**Float SG**	**Mass, (%)**	**Ash, d (%)**	**Ash units**	**Mass, (%)**	**Ash units**	**Ash, d (%)**	**Mass (%)**	**Ash units**	**Ash (%)**	**Mass (%)**	**Mass ±0.1RD %**
F1.30	1.3	13.55	3.21	43.52	13.55	43.52	3.21	100.00	1387.58	13.88	6.78	
S1.30-F1.35	1.35	38.10	7.70	293.59	51.66	337.10	6.53	86.45	1344.06	15.55	32.60	
S1.35-F1.40	1.4	26.46	12.17	322.02	78.12	659.13	8.44	48.34	1050.47	21.73	64.89	77.10
S1.40-F1.45	1.45	9.20	17.16	157.94	87.32	817.07	9.36	21.88	728.45	33.29	82.72	
S1.45-F1.50	1.5	3.33	22.42	74.64	90.65	891.72	9.84	12.68	570.51	45.00	88.99	
S1.50-F1.60	1.6	2.62	29.06	76.14	93.27	967.86	10.38	9.35	495.86	53.04	91.96	6.87
S1.60-F1.70	1.7	0.92	36.78	33.79	94.19	1001.65	10.63	6.73	419.72	62.38	93.73	3.98
S1.70-F1.80	1.8	0.44	43.13	19.08	94.63	1020.72	10.79	5.81	385.93	66.43	94.41	1.72
S1.80-F1.90	1.9	0.36	49.48	17.95	95.00	1038.67	10.93	5.37	366.85	68.35	94.81	1.15
S1.90-F2.00	2	0.35	55.70	19.45	95.34	1058.12	11.10	5.00	348.91	69.71	95.17	
S2.00-F2.00	2.2	0.68	63.77	43.12	96.02	1101.24	11.47	4.66	329.46	70.77	95.68	
S2.00-F2.20	S2.20	3.98	71.95	286.34	100.00	1387.58	13.88	3.98	286.34	71.95	98.01	
Total		100.00										

Table 10. Washability table - Extended form at 2-0.25mm size

1		2	3	4	5	6	7	8	9	10	11	12
Fractions	**Float SG**	**Mass,**	**Ash, d**	**Ash**	**Mass,**	**Ash**	**Ash, d**	**Mass**	**Ash**	**Ash**	**Mass**	**Mass**
		(%)	**(%)**	**units**	**(%)**	**units**	**(%)**	**(%)**	**units**	**(%)**	**(%)**	**±0.1RD %**
F1.30	1.3	42.59	3.08	131.28	42.59	131.28	3.08	100.00	1395.66	13.96	21.30	
S1.30-F1.35	1.35	21.53	8.19	176.36	64.12	307.64	4.80	57.41	1264.37	22.02	53.36	
S1.35-F1.40	1.4	14.57	12.42	180.98	78.69	488.62	6.21	35.88	1088.01	30.32	71.41	45.23
S1.40-F1.45	1.45	6.46	17.04	110.14	85.16	598.76	7.03	21.31	907.03	42.57	81.92	
S1.45-F1.50	1.5	2.66	22.73	60.57	87.82	659.34	7.51	14.84	796.89	53.68	86.49	
S1.50-F1.60	1.6	2.09	29.56	61.83	89.91	721.17	8.02	12.18	736.32	60.45	88.87	5.69
S1.60-F1.70	1.7	0.94	37.99	35.58	90.85	756.75	8.33	10.09	674.49	66.86	90.38	3.60
S1.70-F1.80	1.8	0.57	45.81	25.98	91.42	782.74	8.56	9.15	638.90	69.81	91.13	1.94
S1.80-F1.90	1.9	0.43	51.85	22.47	91.85	805.21	8.77	8.58	612.92	71.40	91.63	1.43
S1.90-F2.00	2	0.42	57.24	24.31	92.27	829.52	8.99	8.15	590.45	72.44	92.06	
S2.00-F2.00	2.2	0.72	64.88	46.62	92.99	876.14	9.42	7.73	566.13	73.28	92.63	
S2.00-F2.20	S2.20	7.01	74.14	519.52	100.00	1395.66	13.96	7.01	519.52	74.14	96.50	
Total		100.00										

Table 11. Overall yield and ash at various SG and different fraction scenario

SG	Fraction at 0.1		Fraction at 0.2		Fraction at 0.3		Fraction at 0.9	
	Yield, %	Ash, %	Yield, %	Ash, %	Yield, %	Ash, %	Yield, %	Ash, %
1.25	49.12	8.38	49.88	8.52	50.63	8.66	55.17	9.38
1.285	61.59	9.07	62.35	9.17	63.11	9.27	67.65	9.82
1.3	65.68	9.31	66.44	9.40	67.20	9.49	71.74	9.99
1.35	74.08	9.96	74.84	10.03	75.59	10.11	80.13	10.52
1.4	77.97	10.37	78.72	10.44	79.48	10.51	84.02	10.88
1.45	80.01	10.67	80.77	10.73	81.53	10.79	86.07	11.14
1.5	81.63	10.95	82.39	11.01	83.15	11.07	87.69	11.40
1.55	82.38	11.09	83.13	11.15	83.89	11.21	88.43	11.53
1.6	83.09	11.27	83.85	11.32	84.61	11.38	89.15	11.69
1.65	83.47	11.36	84.23	11.42	84.99	11.47	89.53	11.77
1.7	83.76	11.45	84.52	11.50	85.27	11.55	89.82	11.85
1.75	83.98	11.52	84.74	11.57	85.49	11.62	90.03	11.91
1.8	84.18	11.59	84.94	11.64	85.69	11.69	90.23	11.98