

What is the Most Efficient Powder Screening Technology for Nickel and Cobalt Alloys

ACFA7004 – RESEARCH METHODS

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Abstract

This study aims to optimise the screening process for a metal powder product to improve yields and reduce manufacturing costs for Wall Colmonoy, a manufacturer of metal alloys. A literature review was conducted to identify the best screening method theoretically. An initial trial between rotary and vibratory screening confirmed the theory of vibratory screening being more efficient. Eight trials were conducted using a vibratory screener to determine the optimum set up taking into consideration feed rate, ultrasonic sieves, lead angle degree, and amplitude setpoint. Trial A8 produced the highest yield and first-time pass, with a maximum yield of 31% achieved, representing a relative improvement of 41%. Benefits of increasing yields include reducing the number of manufacturing batches required resulting in energy savings and increased profits. Safety improvements were also noted using the vibratory screener, reducing manual handling, and improving containment of fugitive dust. The findings of this study have the potential to be applied across Wall Colmonoy's product range to achieve exponential cost savings.

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1. Introduction

Powder metallurgy is a manufacturing technique that involves the production of metal powders and their consolidation into a final product. It has become an increasingly important method in the production of components with complex shapes, high performance, and cost-effectiveness. Wall Colmonoy, a UK-based company, specialises in the manufacture of high-performance nickel and cobalt alloys using powder metallurgy techniques. The company aims to optimise its powder processing operations to increase yields, reduce waste, and improve efficiency. This report provides a literature review to show what technologies are available for screening metal powders. The literature review will describe how rotary and vibratory screening works along with advantages and limitations of each screener. A methodology is developed to compare the screeners. Then, based on the most efficient screener a design of experiment is produced to optimise the screeners parameter in an attempt to maximise yield through increased screening efficiency. This study will follow a Kaizen approach to ensure fairness in the trials and the data gathered will follow sampling standards for segregation avoidance. The results gathered from this study are quantitative results where yields will be calculated from the fraction weights with further analysis coming from laser diffraction to determine whether the product is within specification. Energy analysis will also be conducted to estimate the savings by increasing yields to reduce the number of batches needing manufacturing for the same order quantity. Thus, this report sets out three clear objectives for this project.

A Gantt chart is used to outline the projects activities and to track progress. The timing plan shows how resource limitations effect the final milestone and discusses what can be done to reduce delays.

The report concludes by discussing further limitations in the field and what the next steps are to validate and have confidence in the data. It also recommends that further work should be conducted on migrating methodologies to achieve fine grade powders which are used in newer industries, such as additive manufacturing.

2. Literature Review

2.1. Screening Technologies Available for Metal Powder

There are several different screening technologies available to screen metal-based alloys, especially in the form of Nickel and Cobalt based alloys. The first method is in the form of vibrating sieving, which uses a series of vibrating screens to separate particles of different sizes. The screens are made of wire mesh and the vibrating motion helps to separate particles on their size (April Cooke, 2012).

An alternative screener to vibratory sieving with similar properties is ultrasonic sieving. This technology is based on the principle of using high frequency to separate the particles into sized fractions (Xiaoxu Song, 2013).

Thirdly is air classification, where this type of screener relies on air to separate particles based on their shape. The classifier works by blowing air through a nozzle into a chamber filled with particles through a mesh to create the split fractions (Lanzerstorfer, 2015).

Rotary sieving is a fourth option where particles within a drum are rotated and forces finer particles through a perforated mesh (Dunkley & Yule, 1994).

The final option is using a centrifugal sifter which uses a spinning rotor to force material through a series of meshed screens using centrifugal force to size the material (Pai, et al., 2011).

The above technologies are all beneficial for its intended use. However, with the evolution of additive manufacturing, there is a requirement to make metal powders ultra-fine (below 20 microns). This is problematic for the above technologies apart from vibratory sieving, where it is claimed by (Bilal, 2015) that this technology is able to achieve as low as 6-micron values.

2.2. Location of Trials

Although there are several screening technologies, the basis of this research question will be performed only on rotary and vibratory screening. This is due to the trials being conducted at Wall Colmonoy, a Nickel and Cobalt alloy manufacturer who uses these screeners for their current products. Wall Colmonoy has a long-lasting history across the world with their European Headquarters being in South Wales, where over the years they have been dominant in the metallurgy world for the excellent alloy performance for hard surfacing and several other industries (Manufacturing, 2017).

2.3. Ethical Implications of Nickel

When working with Nickel, it is crucial to have the right protective measures in place as Nickel is a carcinogenic material (HSE, 2019). Thus, adequate extraction needs to be available within the process and the correct personal protective equipment also needs to be available. The Health & Safety Executive also advises that regular monitoring take place by taking Nickel samples for people working in the environment to ensure they are within acceptable limits.

2.4. Factors Affecting Screening

Morphology is a term that categorises the shape of the powder which ranges from highly spherical to agglomerated, as seen in Figure 1. Ideally, all particles would be spherical in shape, however due to variations in the atomising process, the shapes can vary to get un-spherical shapes. This causes problems in the screening processes as poor-quality particles can be within the product, often in elongation form, also known as needles. This causes problems for the end user as blockages can occur in the process (Whiting, et al., 2022).

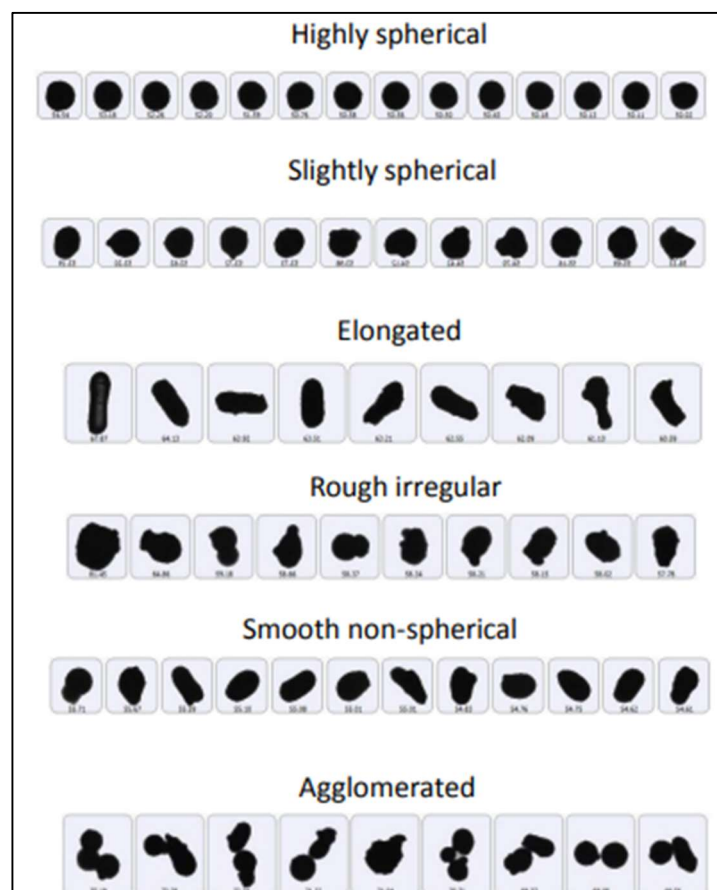


Figure 1 - Examples of Morphology Classifications, Courtesy of (Colmonoy, 2022)

There are other factors aside from morphology and the screening technology used. The first being the screens aperture, which is product dependant. The manufacture of these screens can vary; thus, it is important to check screen sizes from delivery over time to ensure the accuracy of the screen.

Lastly is feed rate. The rate in which material is fed onto the screen can have detrimental impacts to screening efficiency. If the feed rate is too fast, it risks damaging the centre of the screen, and too slow reduces the throughput rate. Thus, it is important to find a balance which is most effective (Dunkley & Yule, 1994).

2.5. Rotary Screening

Rotary screening is a common screening method for separating and classifying particles based on their size and morphology. Rotary screening is based on the principle of rotation, typically around the horizontal plane that uses a 'drum' which has a series of perforated slots, to separate the particles into size fractions. A schematic of rotary screening can be seen in Figure 2. If the particle size is smaller than the aperture the particle will fall through the mesh, otherwise it will stay on the mesh and rotate to an outlet. The drum is powered by a motor and a drive mechanism which can be used in conjunction with an inverter to achieve variable speeds. The motor generates a rotational force that transmits to the drum, causing the particles to move and separate (Dunkley & Yule, 1994). As well as the metal powder industry, this type of screener is suitable for many other industries including agriculture, food processing, pharmaceuticals and many more.

2.5.1. Advantages of Rotary Screening

The screening methods offers several benefits as it is highly efficient, cost-effective and requires minimal maintenance. Rotary screeners are well suited to large volumes of material and can operate at high speeds which makes them powerful for industrial scale manufacturing. The accuracy of this screener is highly efficient to a 60-micron particle size and provides high accuracy in particle classification (Black, 2007).

2.5.2. Limitations of Rotary Screening

Despite its many advantages, rotary screening has some limitations that should be taken into account. The first limitation is the tendency of blinding and pegging of the mesh as this is caused by particles being near or the same size of the meshes aperture, causing the particle to be wedged in the aperture (Ferris, 1998). This screener is limited to screening larger particles, and when screening finer grades, the screener is less efficient.

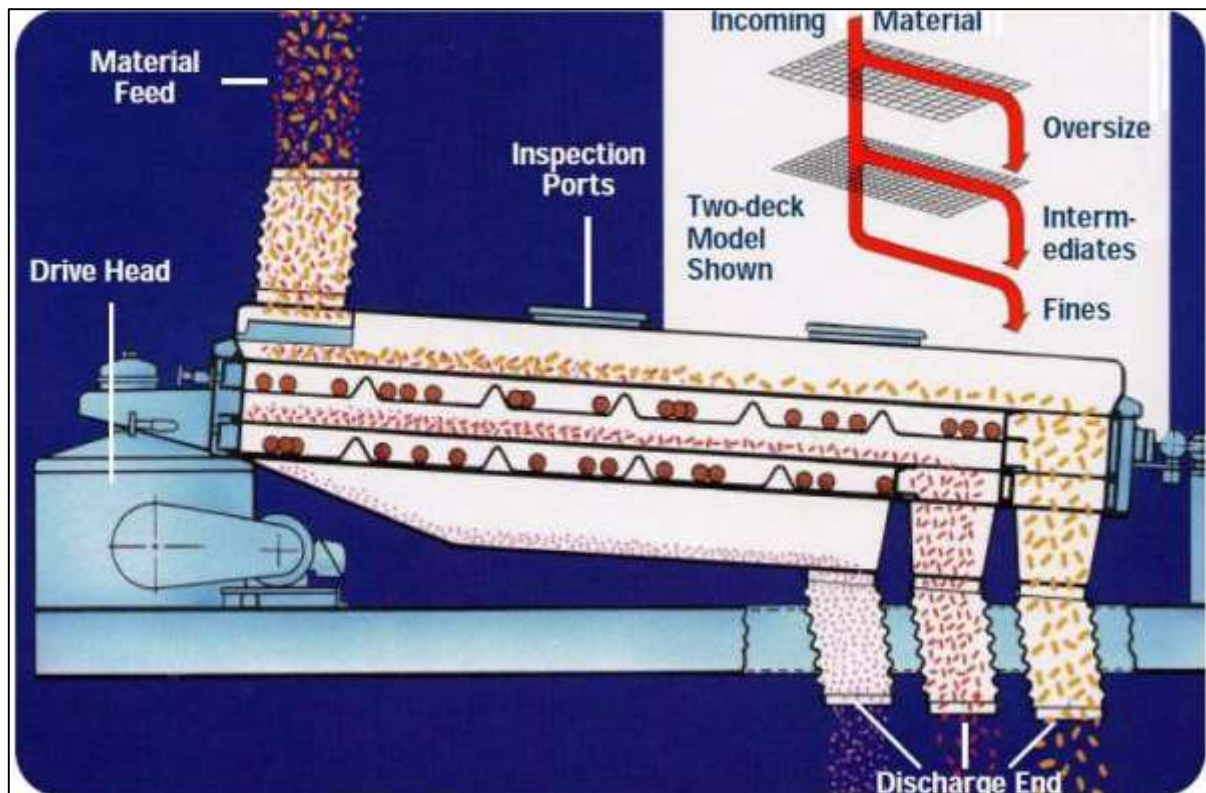


Figure 2 - Schematic of Rotary Screening, Courtesy of (Arcon, 2013)

2.6. Vibratory Screening

Vibratory screening is a widely used method for separating and classifying particles based on their shape and size. As the name states, vibratory screening is based on the principle of vibration where particles are subjected to mechanical vibrations that cause them to move and separate, which can be seen in Figure 3. The mechanical components are similar to those of a vibratory screener and as a motor drives a mechanism causing the vibrations (Bilal, 2015). However, the vibrations pass through a horizontal plane which allows for higher frequencies to be achieved. This screening method is widely used in manufacturing industries, like the rotary screener. This screener is seen more in finer particle industries as the efficiency is far superior to rotary screening when trying to achieve below 50 micron cut points (Dunkley & Yule, 1994).

2.6.1. Advantages of Vibratory Screening

As this technology has improved, there have been advances in deblending technologies to prolong the life of the mesh which can be utilised in this technology. This comes in the form of using ultrasonic sieves, which adds additional frequency vibration through the mesh to dislodge any particles wedged in the meshes apertures. The meshed screens are lightweight and there are apparatus' to make a screen change over a one man operation which allows for more productivity and to minimise downtime (Black, 2007). Due to the construction

and the available ventilation ports, there excellent dust containment which limits the exposure of dust to the atmosphere. Like rotary screening, there are now controls in place that have been developed over the years to have greater controls on throughput to optimise performance (Singh, 2004).

2.6.2. Limitations of Vibratory Screening

Although there are several advantages, there are a couple of disadvantages. The main disadvantages are its limited scalability with larger production volumes. These screening units are compact and limited to its processing throughput (Ferris, 1998).



Figure 3 - Schematic of Vibratory Screening, Courtesy of, (Kay, 2010)

2.7. Summary of Research

To conclude from the research conducted, vibratory screening allows for higher throughput and higher efficiency by prolonging the life of the screen and how the materials move over the area of the screen. Due to the setup, there is less chance of contamination by not needing rubber balls for deblinding. It is suggested that finer cut points can be achieved due to the vibration of the machine. There are more set up parameters available, especially the lead angle and amplitude which controls how powder operates on the screen. With the lighter weight screens, there is less manual involved and there are jigs available to enhance this. Finally, due to the containment and extraction available, there are less fugitive emissions making it a safer working environment, especially when handling Nickel.

3. Methodology

3.1. Screener Comparison Trial

From the established screening technologies, it was determined to understand which of the two screeners, rotary screening and vibratory screening, differ in practice. It is known from the literature review that rotary screening is more efficient for screening finer grades of powder (sub 50 micron).

3.1.1. Rotary Screener Trial Set Up

A small-scale trial was set up to prove the theories. A batch of 450kg of a Nickel based alloy was manufactured with a d50 value of 55 microns. The batch was first processed down the rotary screening routes with the feed rate set to 300kg per hour and a 60-micron aperture screen was used. The rotary screening set up can be seen in Figure 4.



Figure 4 - Rotary Screener Set Up at Wall Colmonoy

3.1.2. Homogenising the Batch

Once the batch was screened through this route, the fractions from the trial, product, fines, and oversize were blended back together following Wall Colmonoy's blending procedure. By including this step, it ensures the batch is homogenised to prevent any false readings during the vibratory screener trial which could be caused by segregation in the hopper, commonly known as 'rat holing'.

3.1.3. Vibratory Screener Trial Set Up

The batch was then processed through the vibratory screener route and the results recorded. The rotary screener from the trials can be seen in Figure 5.



Figure 5 - Vibratory Screening Install at Wall Colmonoy

3.1.4. Trial Parameters

To keep fairness between the screeners, several parameters were kept the same to have a direct comparison. The first parameter was the screens aperture and a 60micron screen was used on both screeners. Although, this is not standard practice at Wall Colmonoy. With Wall Colmonoy's vast knowledge in this area, procedures have been developed for each product where a different screen size would be used on the products lines to meet the specification. However, as this initial study is to compare the screeners efficiencies at comparable parameters, meeting the products specification is not important. This will come at a later stage to optimise the screeners parameters to meet the specification on a right first-time basis. The second parameter controlled was the federate onto the screen. This was set to 300kg per hour on both machines. For completeness, the same operator was used to set up and run the machine with the data being recorded by the same engineer.

3.2. Atomising Particle Size Distribution

The data collection would be comprised of two key areas. The first was weighing the fractions from the screener to calculate the yield from the study and compare the results. The second was to take samples from each fraction, analyse the sample using laser diffraction to determine if there was any product within the oversize and fines by comparing this to the atomised distribution and the expected yield. The graph shown in Figure 6 represents the particle size distribution from the atomised sample. This bell curve establishes the percentage of particles at each micron size. This allows the theoretical yield to be calculated by summing the percentage of material that is within the specification bands, as shown in Table 1. Although, for ease of viewing, the percentiles, as shown in appendix 1, Table 3, can quickly determine how much material is in the d10, d50, and d90 bands to allow for a quick understanding of the particle size distribution.

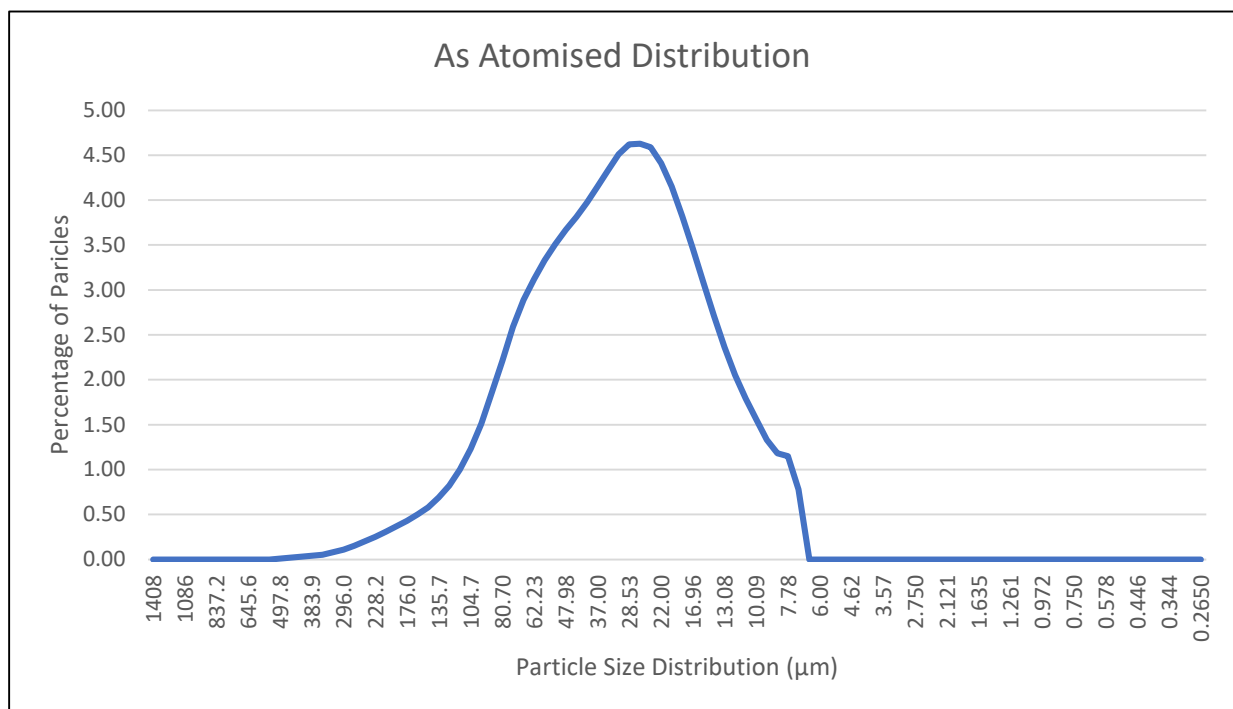


Figure 6 - Particle Size Distribution of Atomised Batch for Study

Size(um)	%Chan
62.23	3.12
57.06	3.33
52.33	3.51
47.98	3.57
44.00	4.81
40.35	4.97
37.00	4.15
33.93	4.33
31.11	4.51
28.53	4.62
26.16	4.63
23.99	4.59
22.00	4.41
20.17	4.15
Total	58.70

Table 1 - Distribution for Theoretical Yield

3.3. Representative Sampling

It was important to have representative samples to ensure the sample was free from any segregations. ASTM B215 Sampling of Metal Powders states the best practice for a representative sample was during a stream by taking a sample at the start, middle and end and blending the sample together (International, 2020). Due to the sample area of the fractions being too small to do this, a sample thief as shown in the example from Figure 7, was used to mimic the start, middle and end procedure. The standard does state a scoop sample can be taken from the top of the hopper; however, this is not advised due to risk of segregation build up and false data being produced.



Figure 7 - Example of Sample Thief, Courtesy of (Systems, 2015)

3.4. Screener Trial Results

From the study outline above, it can be clearly seen from the summary data in Table 2 that the vibratory screener is more efficient from the small-scale trial conducted, as per the research suggested. The particle range is the specification for this product, with minimum and maximum ranges.

Particle Range	%Min	%Max	Rotary	Vibrating
>75	0.0%	0.0%	0.0%	0%
75-63	0.0%	0.2%	0.1%	0%
63-53	0.0%	10.0%	3.4%	0%
53-45	15.0%	35.0%	25.8%	10%
45-38	17.6%	75.0%	36.9%	40%
38-20	15.0%	40.0%	33.4%	45%
<20	0.1%	0.4%	0.5%	5%

Table 2 - Results of Rotary vs Vibratory Screening Compared to Specification

3.5. Optimisation of Vibratory Screening

Following this result, a design of experiment along with a planned Kaizen activity was established to further optimise the vibratory screeners parameters to increase yields and right first-time percentages. This new study allows for more of the screeners parameters to be controlled, such as the feed rate, amplitude, lead angle and a deblending process in the form of ultrasonic screens to prolong the screens life expectancy.

3.5.1. Lead Angle

The lead angle, also known as the angle of inclination or angle of attack, is the angle between the horizontal plane and the line of force generated by the vibratory motor. Its value determines the direction of material movement on the screen surface, and can be modified to optimize screening performance. Increasing the lead angle produces a more aggressive screening action, while decreasing it results in a gentler screening action. In a separator with a 0° lead angle and fed in the centre of the screen, material tends to move around the edge of the

screen without fully discharging, which is typically insufficient for most applications as shown in Figure 8.

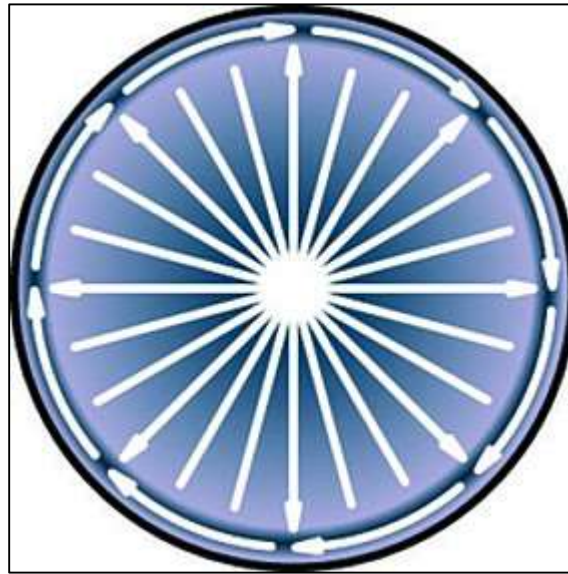


Figure 8 - Example of Lead Angle at 0° , Courtesy of, (Brock, 2011)

Lower lead angles move material radially from the centre to the edge of the screen, while mid-level lead angles create a spiral pattern that maximises the material's time on the screen surface.

A lead angle of 30° - 35° , shown in Figure 9 delivers the most efficient screening pattern, while higher lead angles can cause oversize material to turn back towards the centre of the screen reducing discharge efficiency.

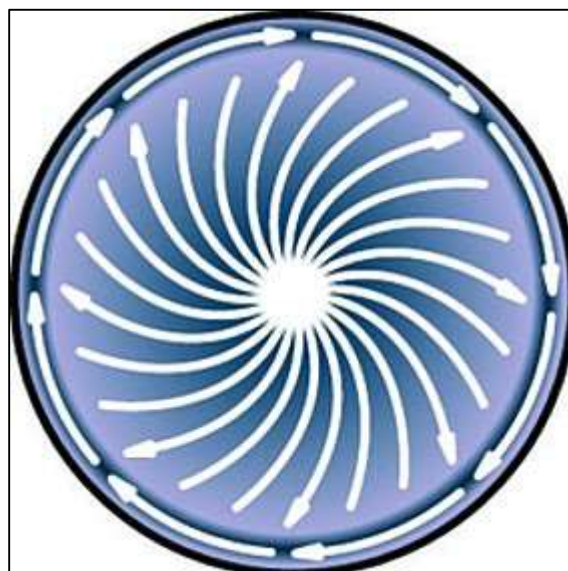


Figure 9 - Example of Lead Angle Between 30° and 35° , Courtesy of (Brock, 2011)

Some applications may require a higher lead angle, such as scalping, where the material needs to be held on the screen longer.

3.5.2. Amplitude

The amplitude refers to the maximum displacement of the screen surface from its resting position, indicating the strength of vibration applied to the screen. Its adjustment controls the screening intensity and is measured in terms of peak-to-peak displacement. A larger amplitude provides a more vigorous screening action, while a smaller amplitude produces a less intense screening action.

3.6. Objectives

From this project, there are 3 objectives to be met, to compare rotary screening and vibratory screening in practice, to determine the most efficient and suitable screening technology and finally, to optimise the most efficient screener to increase yields and productivity.

4. Results

4.1. Overview of Results

From the methodology stated for the trials through the vibratory screener, a total of eight runs were conducted to determine the optimum set up taking into consideration the feed rate being 150kg per hour or 300kg per hour, whether ultrasonic sieves were to be used, the lead angle degree and the amplitude setpoint. However, it is difficult to determine how much of an effect the ultrasonic sieves have as the screens are designed to be highly efficient when processing large tonnage. Whereas in this study, only a 450kg batch was processed, with the screen being cleaned after each run. Figure 10 shows a summary of each trial and the parameters used.

A1 - Standard Feed Rate, Ultrasonics Off, Lead Angle 60, Amplitude G:G
 A3 - Standard Feed Rate, Ultrasonics Off, Lead Angle 90, Amplitude F:F
 A6 - Standard Feed Rate, Ultrasonics On, Lead Angle 60, Amplitude F:F
 A8 - Standard Feed Rate, Ultrasonics On, Lead Angle 90, Amplitude G:G
 B2 - Non-Standard Feed Rate, Ultrasonics On, Lead Angle 60, Amplitude G:G
 B3 - Non-Standard Feed Rate, Ultrasonics On, Lead Angle 90, Amplitude F:F
 B5 - Non-Standard Feed Rate, Ultrasonics Off, Lead Angle 60, Amplitude F:F
 B7 - Non-Standard Feed Rate, Ultrasonics Off, Lead Angle 90, Amplitude G:G

Figure 10 - Parameters Used for Trials

The graph displayed in Figure 11, shows the results from each trial comparison and the sieved fractions in a percentage by dividing the weight in the fraction hopper by the atomised weight.

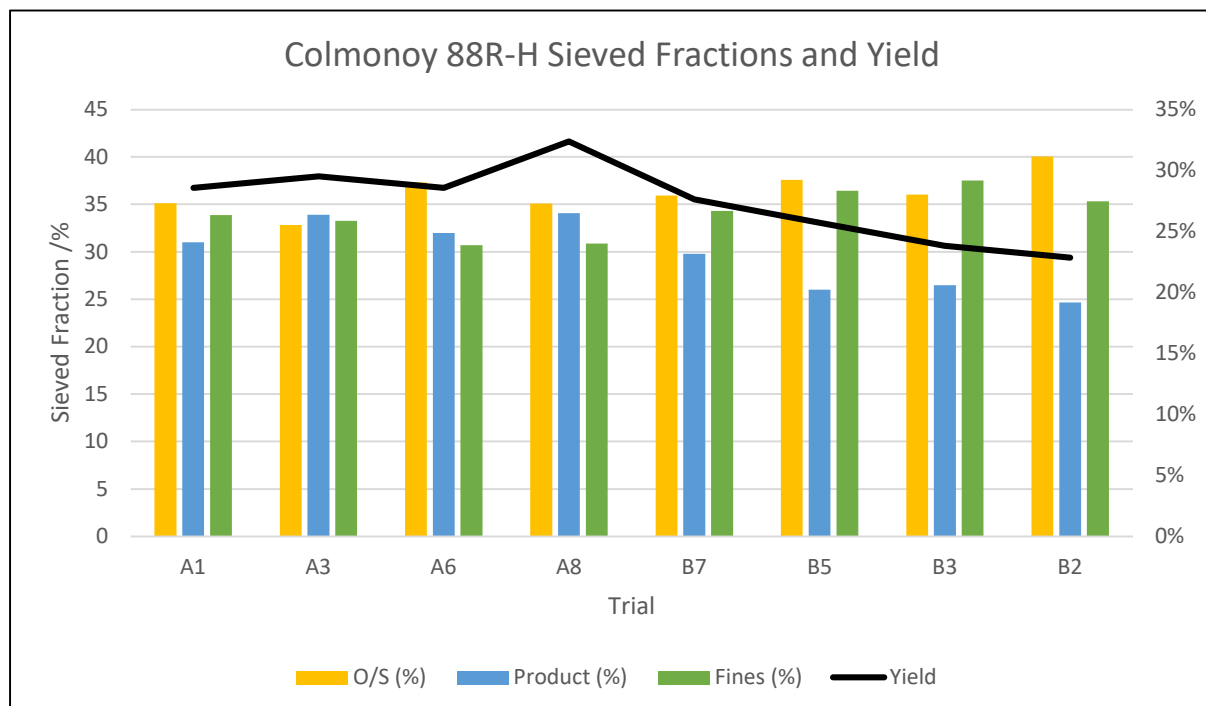


Figure 11 - Summary of Results from Trials

4.2. Most Successful Trial

The trial A8 produced the most yield and a right first-time pass. One of the reasons why this occurred was due to retaining product rather than losing the product to fines or oversize. From the graph shown in Figure 12, it can be seen from the particle size analysis, there is still crossover of product in the oversize and fines. However, compared to the other trial parameters, trial A8 had the most improved performance. Arguably, trial A3 had retained more product, however this was out of specification, resulting in rework which would be required to meet specification. The full particle size analysis from each trial can be seen in appendix two to eight.

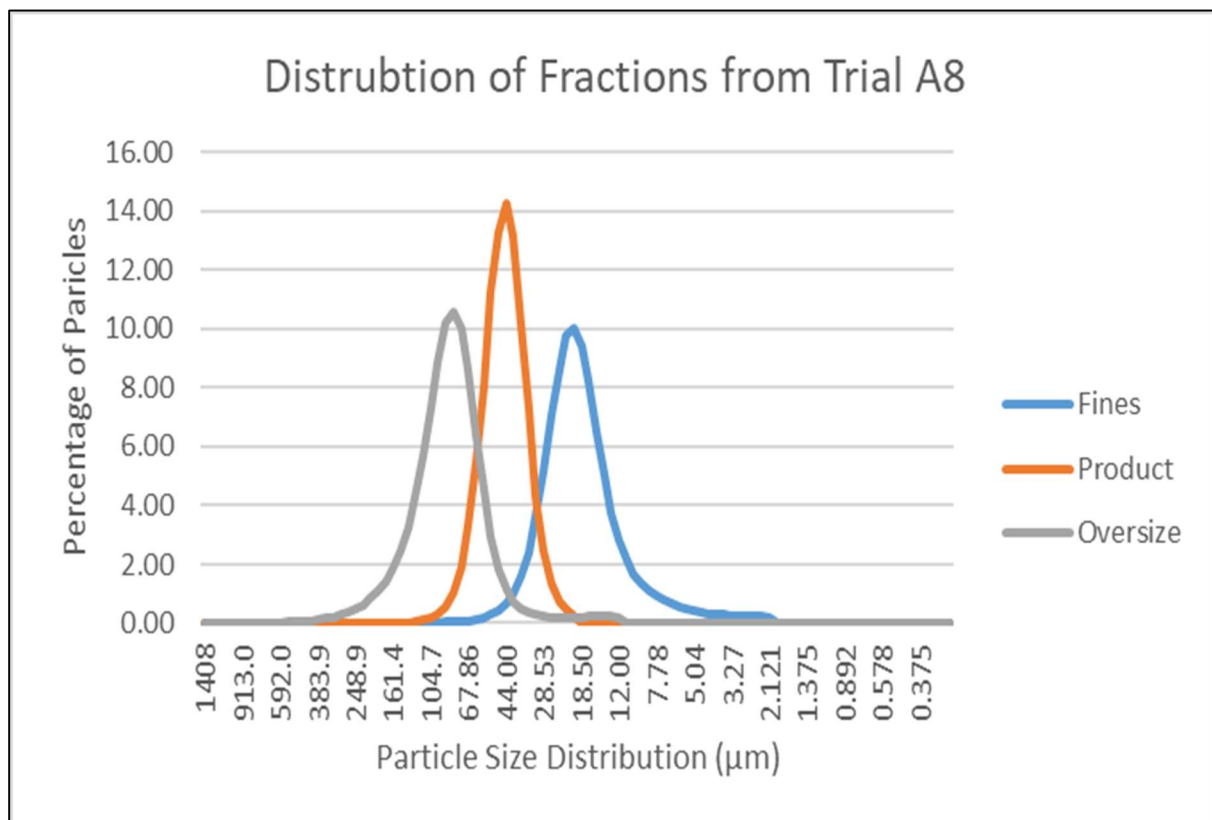


Figure 12 - Distribution of Fractions from Trial A8

4.3. Screening Efficiency

When investigating screening efficiency, trials A3 and A8 stood out as being the most efficient with 58% screening efficiency. Figure 13 shows how the screening efficiency was calculated using the product and potential yield for trial A8, along with the split of product and fines percentages. In appendix two to eight the calculations are shown with the lowest screening efficiency being 43% in trial B2. These initial trials prove how set up optimisation is crucial in improving yields in screening metal powders.

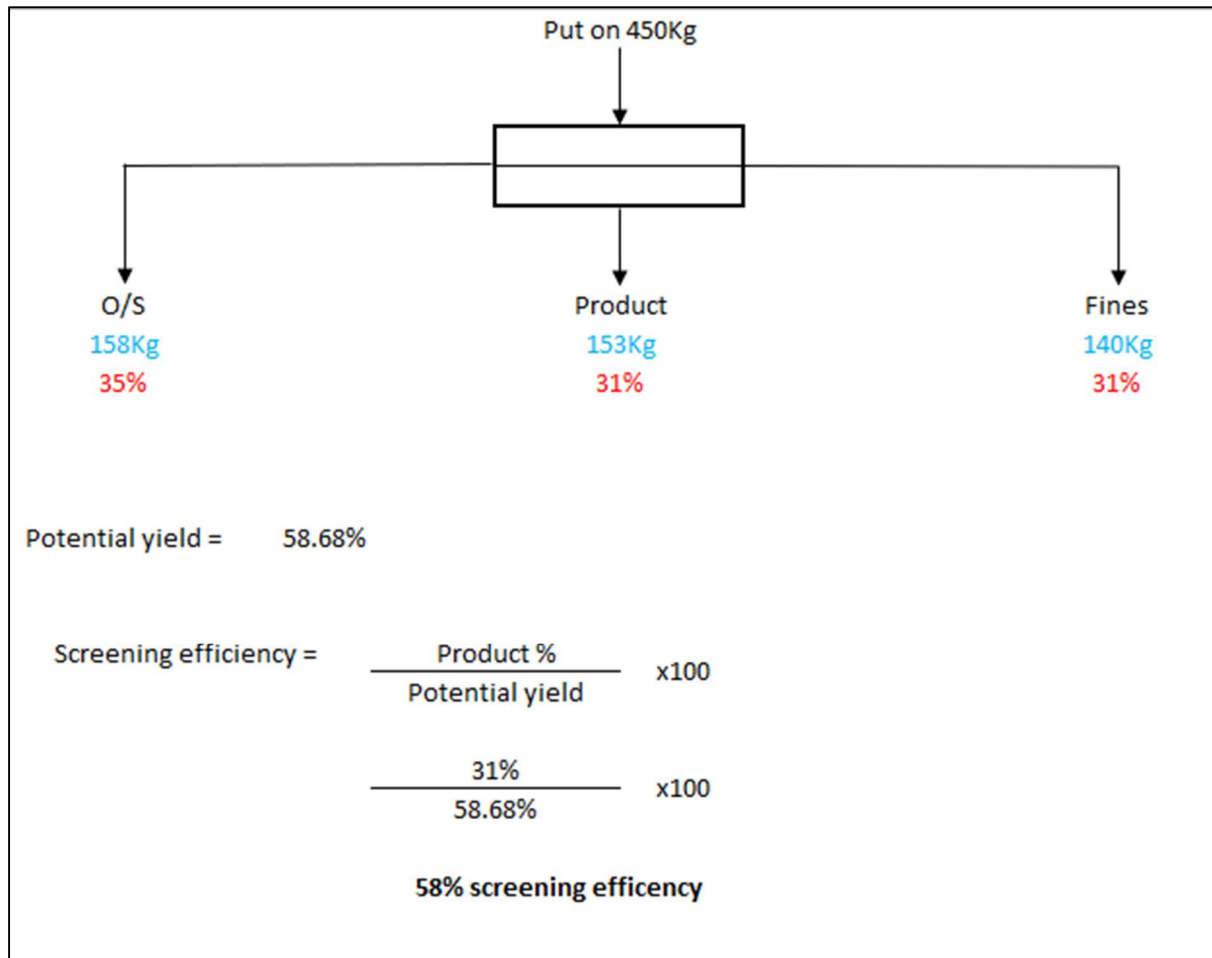


Figure 13 - Screening Efficiency from Trial A8

4.4. Yield Calculations

The yield was calculated by how much products there was within the product hopper and was to specification on a right first-time pass. The maximum yield achieved from the optimisation trials was 31% which included a first-time pass, from trial A8. This improvement of 9% on yield actually equated to a 41% relative improvement. Relative change is a measure of the difference in value of an indicator between two periods, expressed as a percentage. It is calculated by subtracting the value of the indicator in the first period from the value of the indicator in the second period, dividing the result by the value of the indicator in the first period, and then multiplying by 100% to express the change in percentage terms. This can be represented mathematically using the formula:

$$\text{Relative Change} = (\text{Final value} - \text{Initial value}) / \text{Initial value} * 100\%$$

4.5. Benefits to Yield Increase

One of the benefits to increasing yields, is the reduction in manufacture batches to achieve the same end product quantity. For this product, the average product quantity is 4,950kg with an average yield of 22%, this equates to needing 50 batches to meet the order quantity. However, an increased yield to 31% only requires 36 batches of 450kg to be manufactured, which is a reduction of 14 batches. On energy alone from covering the furnace consumption to melt the raw material, the drying of the slurry from water atomising and finally screening the product, this reduction of 14 batches equates to a monthly saving of £4,282 and a yearly saving of £51,385 per year. This saving does not include other savings such as a reduction in Nitrogen consumption, operators' movement and processing costs, thus this saving would be marginally higher. This cost also includes the throughput performance change, as to meet the specification of rotary screener the throughput is limited to 150kg per hour, compared to 300kg per hour on the vibratory screener, a 100% relative improvement. This allows for more products to be processed to expand the screening production to meet current and future increased demands without the need for large capital investments. Apart from the savings stated, the more efficient the process is, the more profit the organisation can acquire, due to the reduction in processing costs. This also allows Wall Colmonoy to be more competitive as it allows a more aggressive price for the product to be set compared to competitors to drive successful relationships with current buyers and acquire new business opportunities.

Wall Colmonoy has a vast product range, up to 100 product codes. Although not all of the products are made at the same time, the production rate is atomising 100 tonne per month. If yields were to increase across the board on products, the savings can be exponential, putting Wall Colmonoy in a competitive and profitable position.

4.6. Safety Improvements

As shown in Figure 3 there is more extraction from the equipment as well as the hoppers when compared to Figure 2. This further ensures the safety in the workplace when containing fugitive dust. There are also safety improvements by using a vibratory screener in relation to manual handling. When conducting changeovers, the screen weight is light by 20kg reducing from 25kg to 5kg. There are also lifting apparatuses available for vibratory screeners to make quicker changeovers to reduce the amount of downtime.

4.7. Timing Plan

A Gantt chart was set out for this project to outline when activities were to take place, along with the milestones for the research proposal and subsequent presentation as shown in Figure 14.

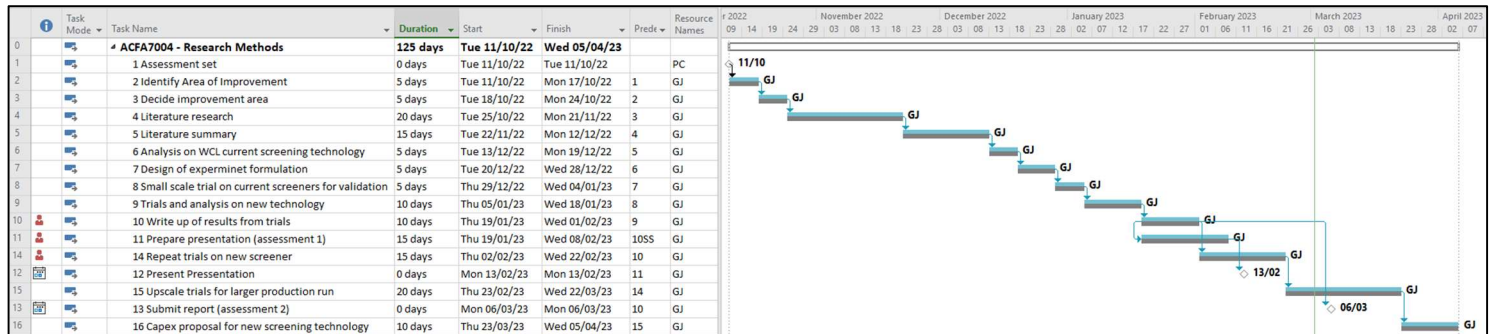


Figure 14 - First Revision on the Projects Gantt Chart

The project was on track until March 2023, where two deadlines were pushed back due to resource availability, both at Wall Colmonoy and the University of Wales Trinity St David. These setbacks pushed the deadline for the proposal back from the 6th of March 2023 to the 31st of March 2023 and a Capital Expenditure submission back from the 5th of April 2023 to 2nd June 2023, as shown in Figure 15.

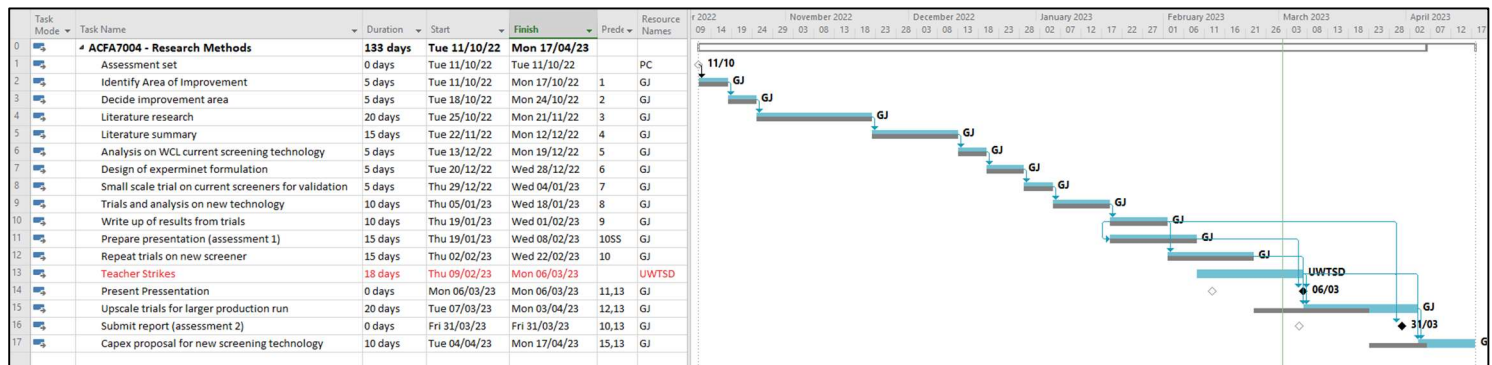


Figure 15 - Revised Gantt Chart to Account for Delay

In the Gantt charts, the grey back indicates a baseline and the blue bar shows the time allocation. This allows comparison between the task duration and baseline, and when slippage happens, it identifies areas when time could possibly be exonerated to minimise time passed the deadline. In larger projects, this methodology proves critical to delivering on time projects where there is a greater likelihood of project slippage. Although, on initial look the results are promising, there needs to be further work to validate and have full confidence in the data. This has been considered in the timing plan to conduct a repeatability study before upscaling to larger production runs to measure performance. The project will conclude phase one by applying the data and cost into a capital expenditure request to purchase a second vibratory screener to replace one of six rotary screeners at Wall Colmonoy.

5. Conclusion

In conclusion, screening metal powders is a critical process in the manufacturing industry, especially in the production of Nickel and Cobalt-based alloys. The literature review highlighted the importance of improving product yield in industrial processes to reduce waste and increase profitability. It also discussed various methods to achieve this, including process optimization, equipment modification, and raw material selection. The methodology described the specific approach taken in this project to improve yield in a metal powder atomizing process at Wall Colmonoy. The project first conducted a comparison trial to prove the theory of vibratory screening being more efficient than rotary screening, which was achieved.

The project then utilised a vibratory screener and conducted eight trials to optimise feed rate, lead angle degree, and amplitude setpoint. The results showed that the maximum yield achieved was 31%, representing a 41% relative improvement, which would result in significant cost savings and increased competitiveness for Wall Colmonoy. This study shows that increasing the yield to 31% would require 36 batches of 450kg, a reduction of 14 batches compared to the average yield of 22%, which would need 50 batches to meet the same order quantity. This reduction leads to significant cost savings, such as a monthly saving of £4,282 and a yearly saving of £51,385 on energy consumption alone, not including other savings such as Nitrogen consumption and operator costs. Moreover, the vibratory screener's higher throughput rate of 300kg per hour, compared to 150kg per hour on the rotary screener, offers a 100% relative improvement in throughput performance. This improvement allows for more products to be processed to meet current and future increased demands without requiring significant capital investments. The increased efficiency in the screening process also makes Wall Colmonoy more competitive by allowing a more competitive price for the product to be set at compared to competitors, which could lead to acquiring new business opportunities and building a good reputation. By complying with sampling standards, it allowed the samples to be collected and analysed fairly.

5.1. The Need for Further Work

Although the study proved successful on a one batch basis, the data needs further validation. The trials should be repeated with another batch, and the batch should be repeated a further three times. If the results prove to be successful, then this should be upscaled to a full production run, to validate this study. There also needs to be further work in combining two technologies, air classification and vibratory screening. There needs to be an understanding for a screening method for having high efficiency screener when the d50 is 5 microns or below, which is required for the additive manufacturing industry, which is growing exponentially.

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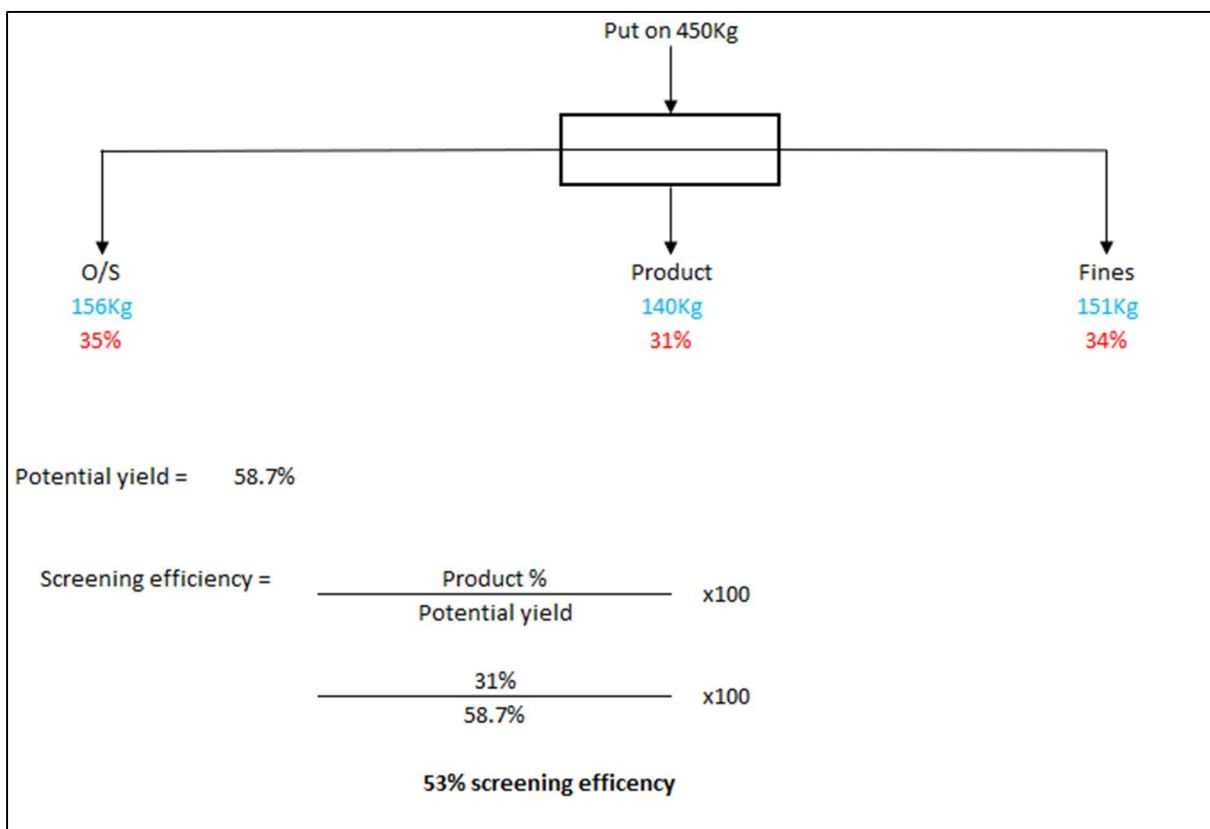
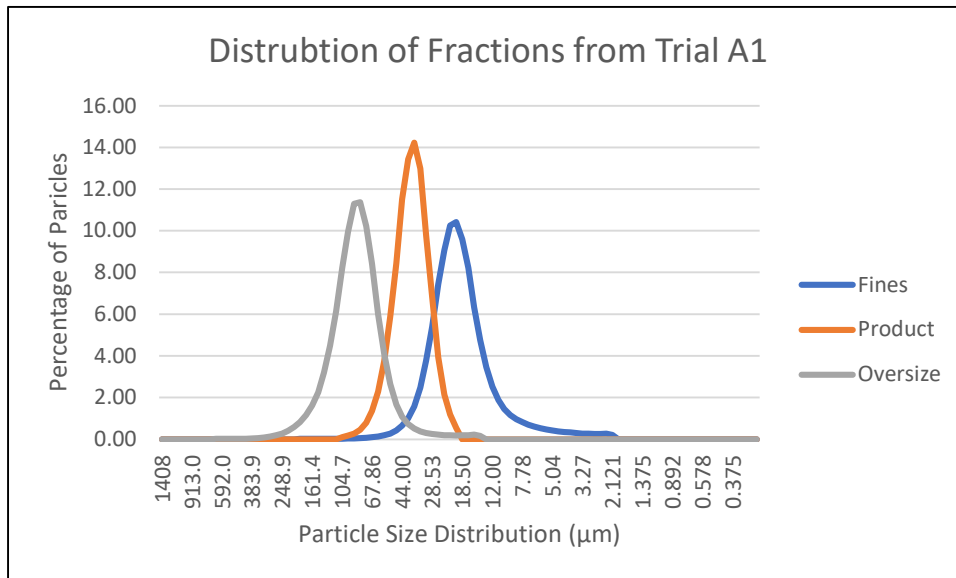
Appendices

Appendix 1 – Percentiles of Atomised Distribution

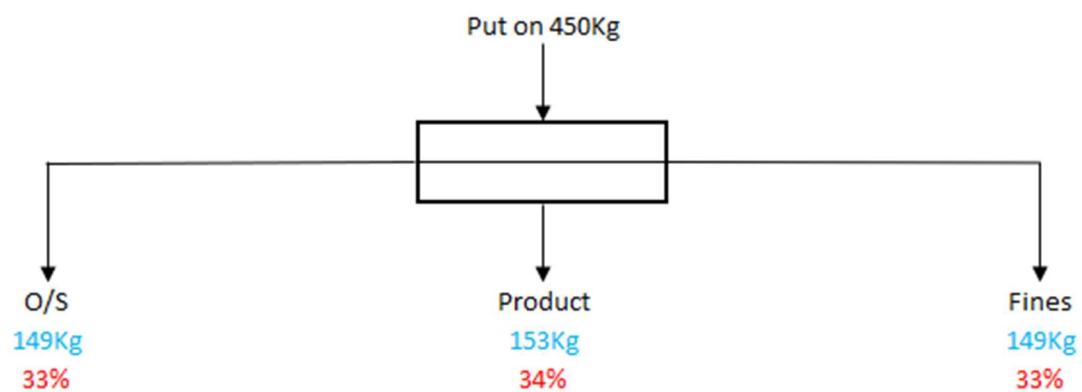
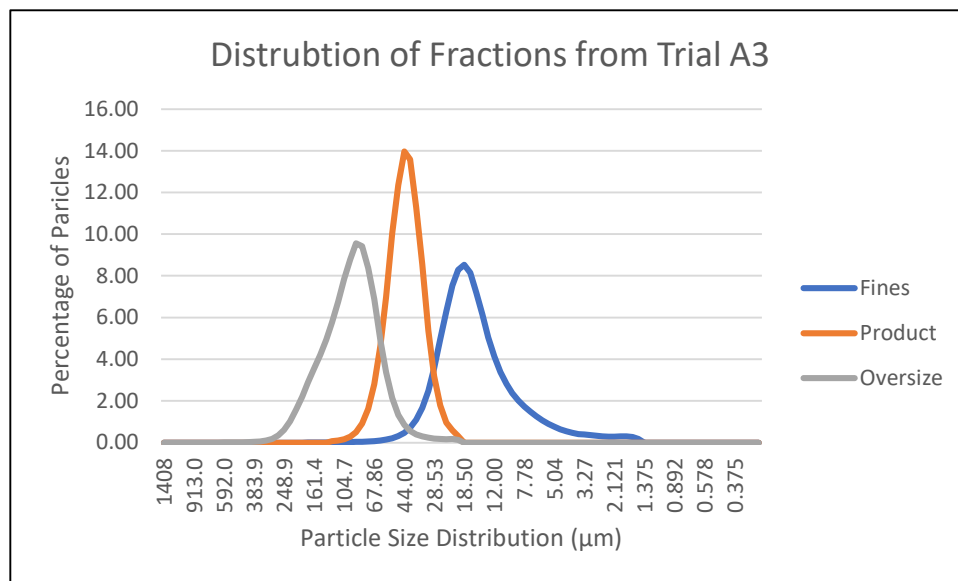
Percentile	Size(um)
d10	12.07
d20	16.38
d30	20.41
d40	24.71
d50	39.81
d60	46.48
d70	55.62
d80	68.70
d90	91.51
d95	110.3

Table 3 - Percentiles of Atomised Distribution

Appendix 2 – Trial A1



Appendix 3 – Trial A3



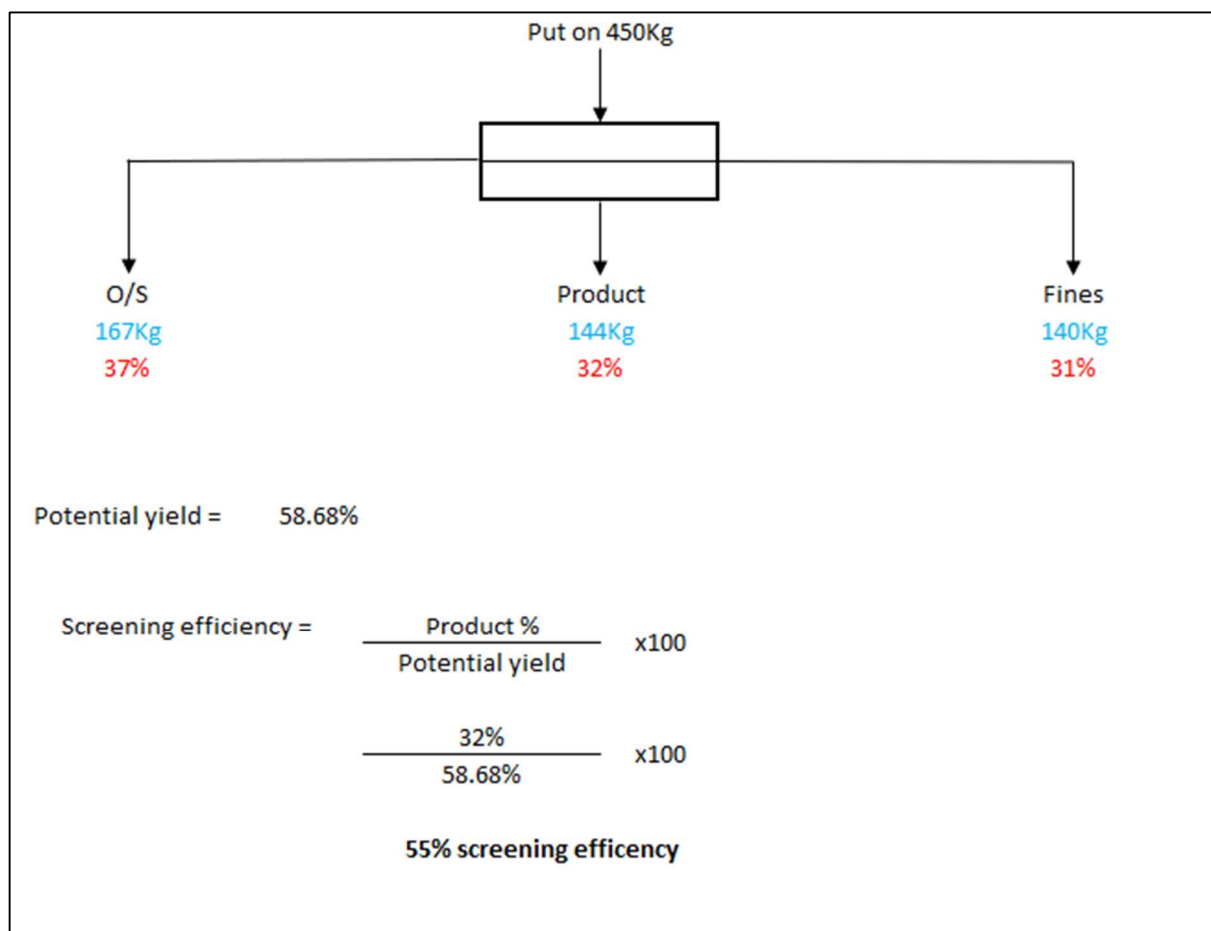
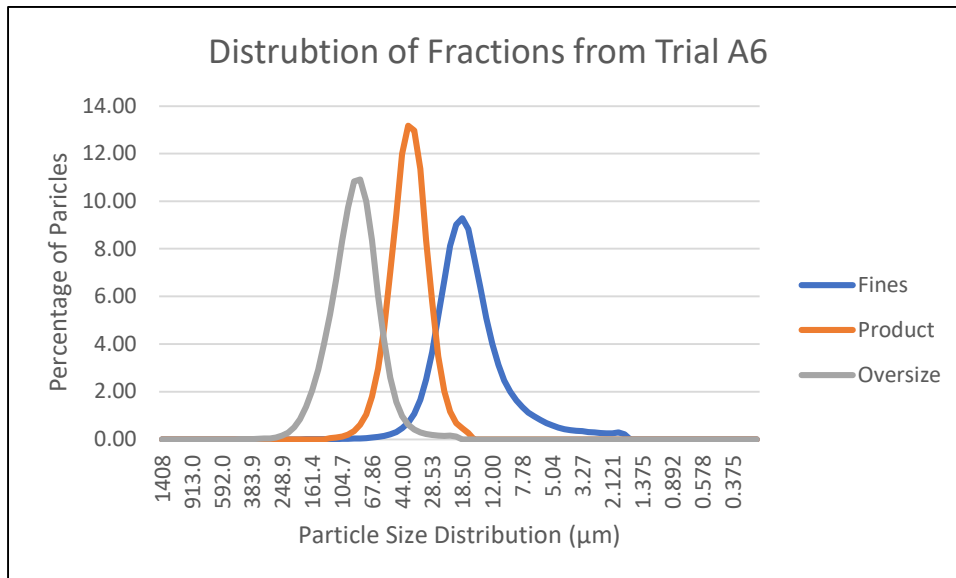
Potential yield = 58.68%

$$\text{Screening efficiency} = \frac{\text{Product \%}}{\text{Potential yield}} \times 100$$

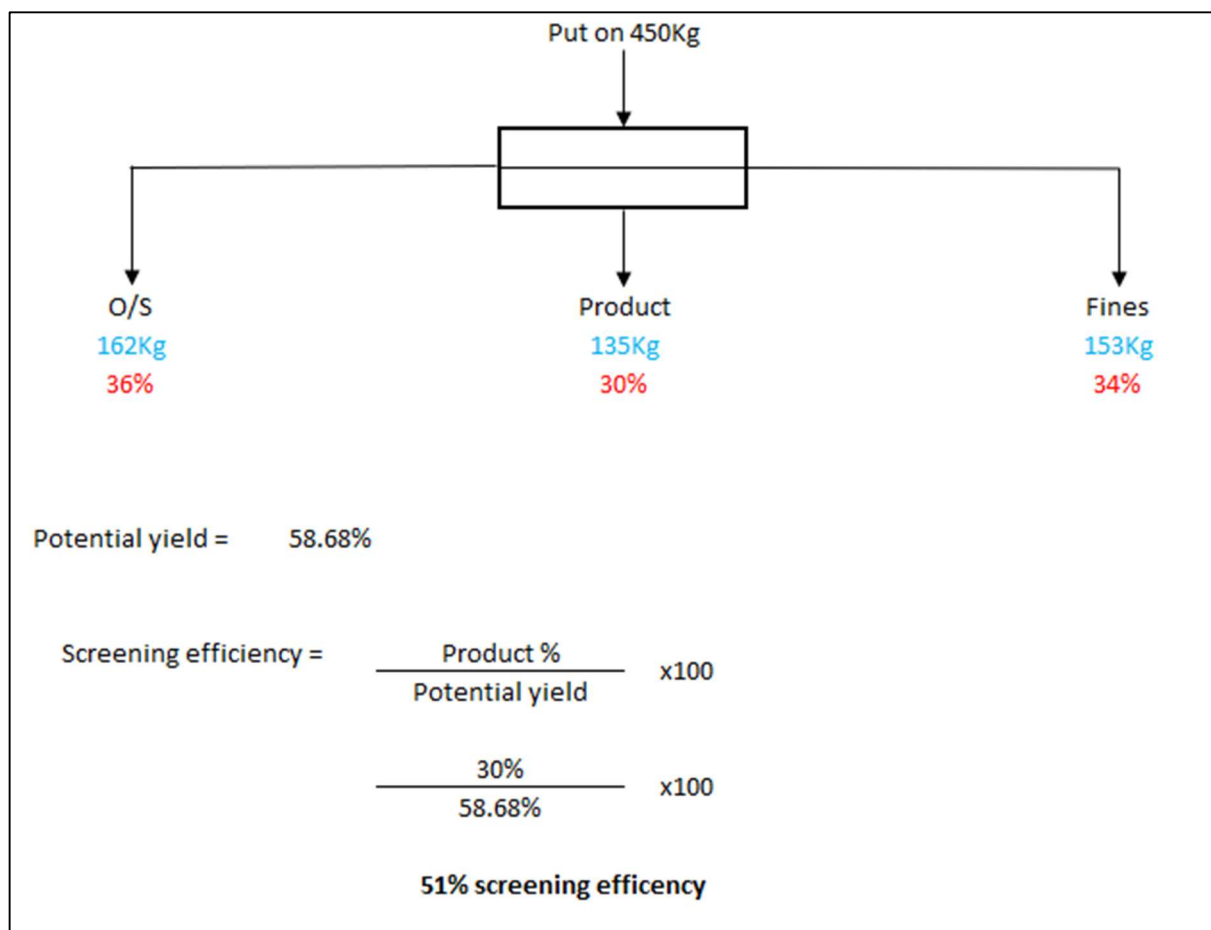
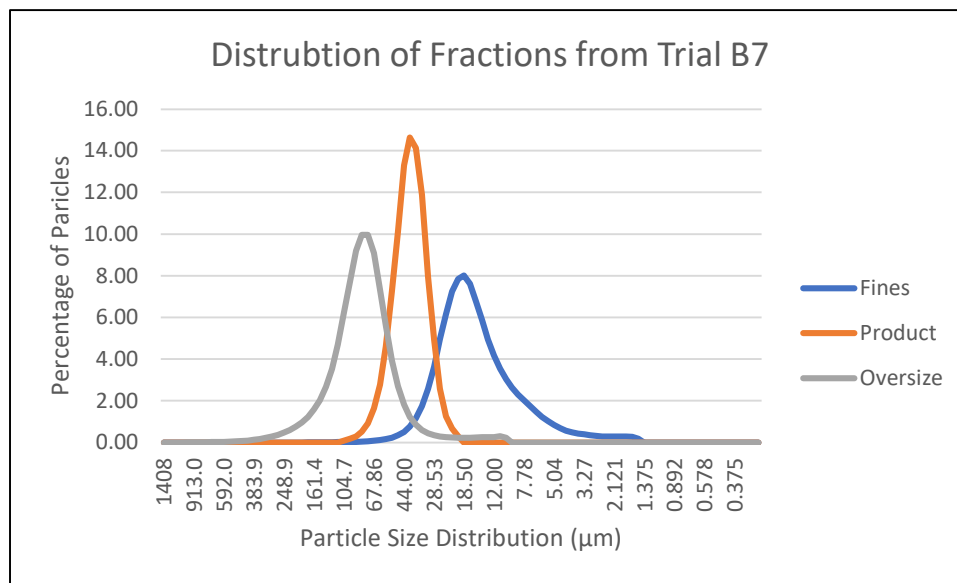
$$= \frac{34\%}{58.68\%} \times 100$$

58% screening efficiency

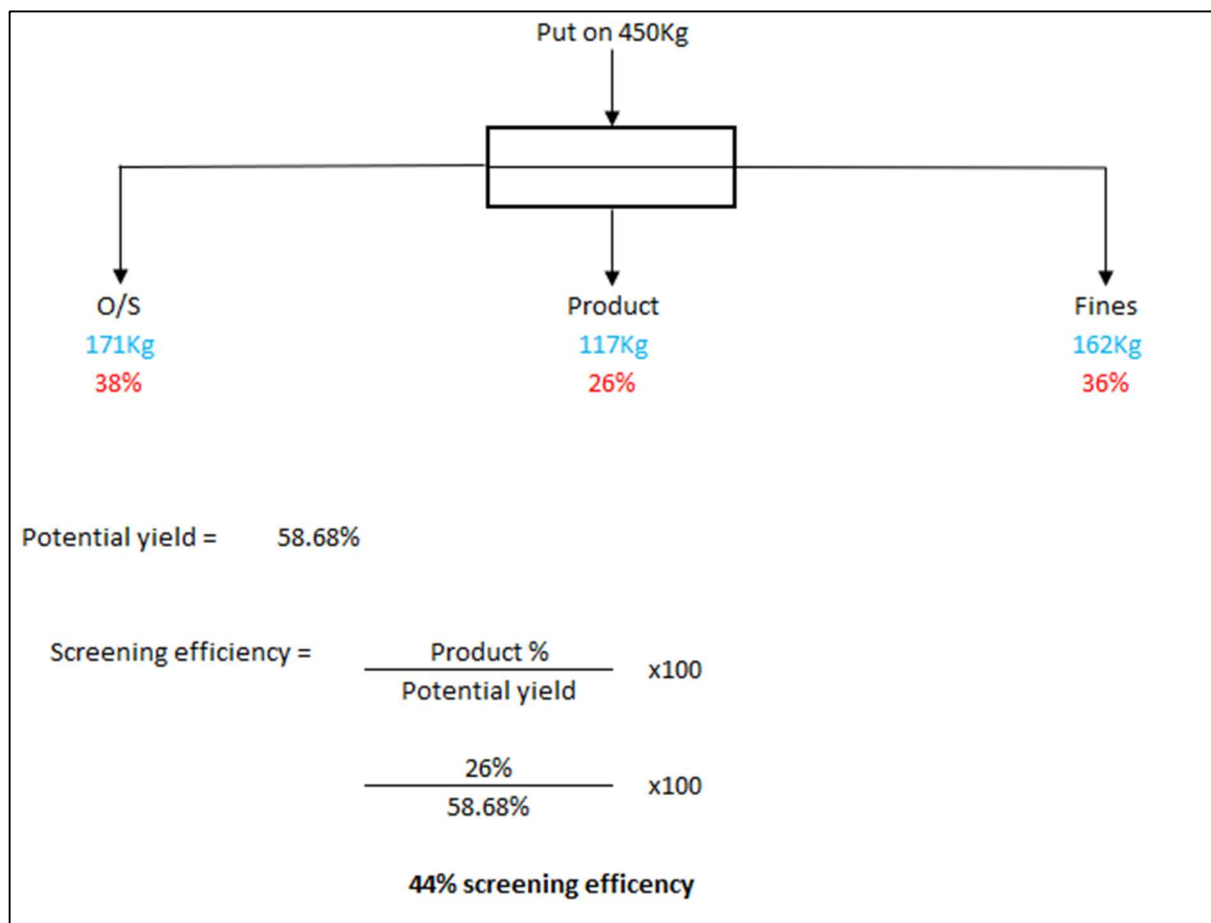
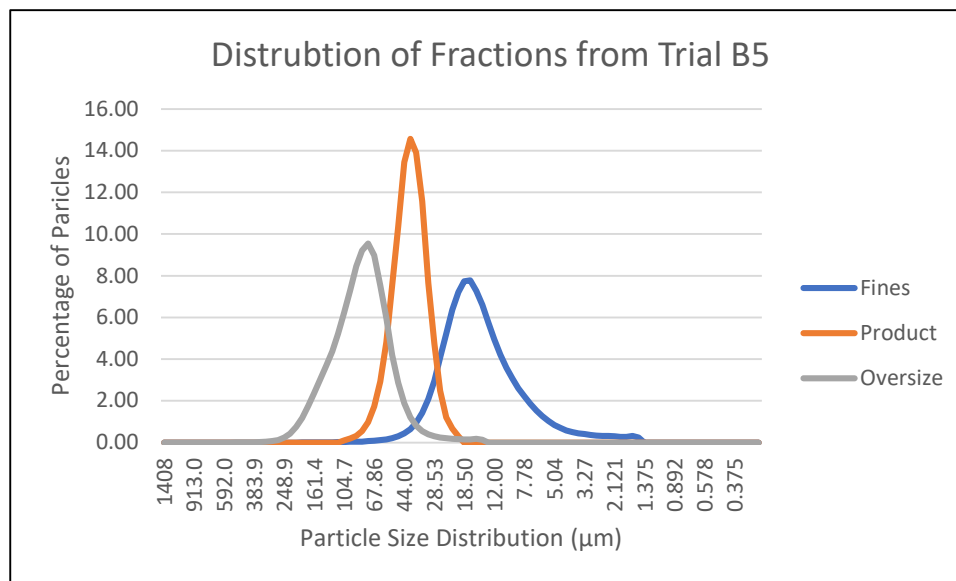
Appendix 4 – Trial A6



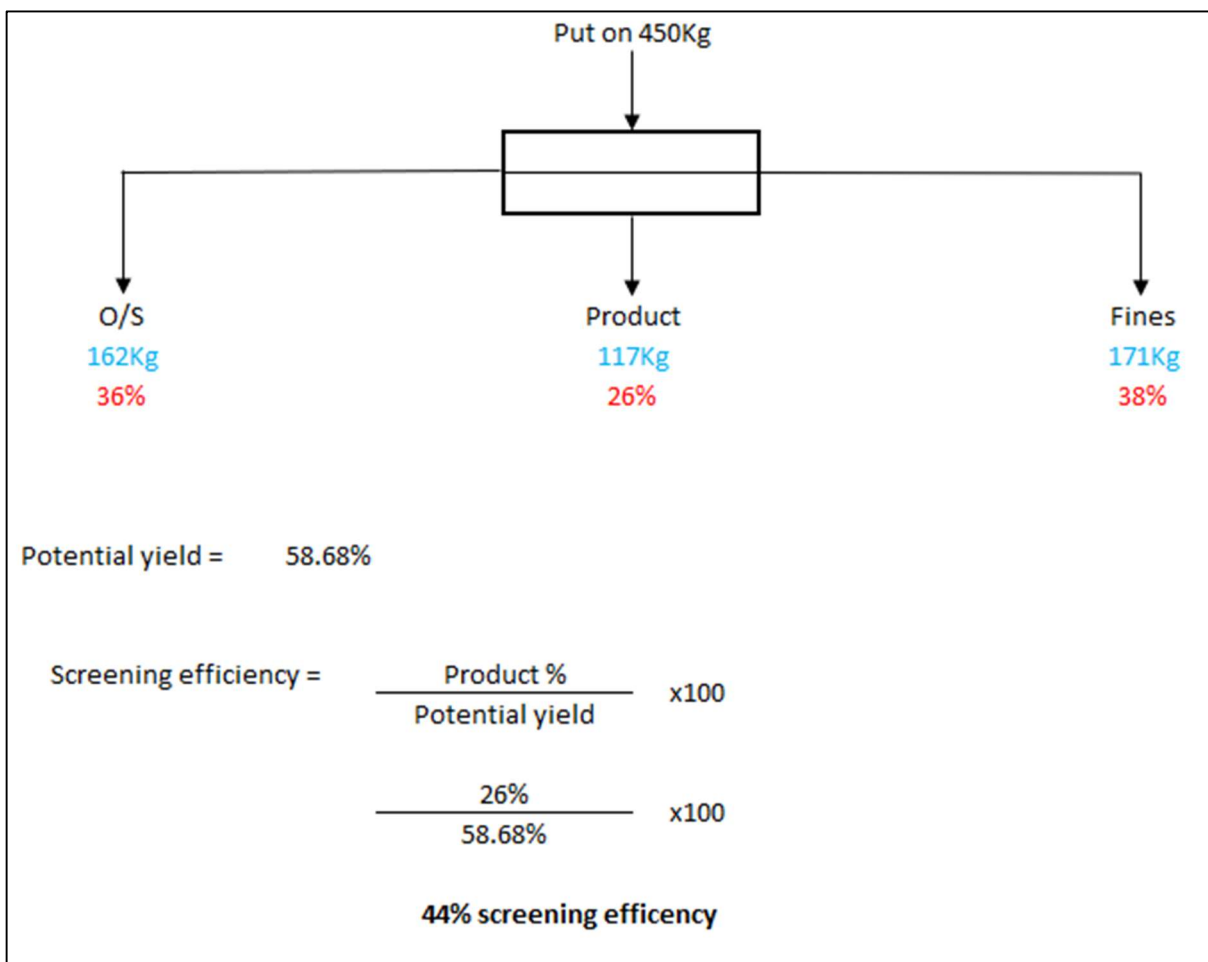
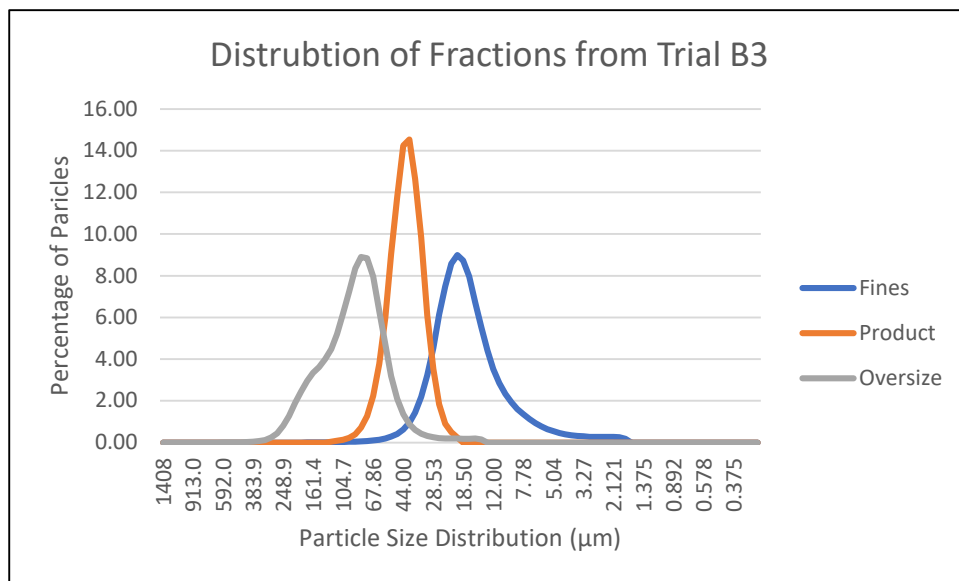
Appendix 5 – Trial B7



Appendix 6 – Trial B5



Appendix 7 – Trial B3



Appendix 8 – Trial B2

