

INCREASING THE SCREENING EFFICIENCIES OF NICKEL BASED SUPER ALLOYS FOR NEXT GENERATION TECHNOLOGIES

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Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Gavin John

Date: 12th January 2025

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Abstract

Nickel and cobalt-based alloys are critical to aerospace, automotive, and additive manufacturing due to strength, corrosion resistance, and thermal stability. Ensuring precise particle size distribution (PSD) during production is essential, as it directly impacts throughput, yield, and right-first time (RFT) quality. Traditional methods like rotary screening often fail to meet the demand for ultra-fine powders below 20 microns, lacking precision and efficiency.

This study evaluates key screening methods. Ultrasonic vibratory screening excels at handling +20-micron powders. Rotary screening supports high throughput for coarse materials but struggles with mesh blinding and inefficiency for finer particles. Air classification is the most effective for sub-20-micron powders, achieving precise PSDs with aerodynamic mechanisms, through less effective coarser materials.

A hybrid approach combining air classification and ultrasonic vibratory screening overcomes individual limitations, doubling throughput from 150 kg/hr to 300 kg/hr and improving RFT from 58% to 81%. This system yields annual savings of £250,000 by reducing labour, energy costs, yield losses, and melt inefficiencies. With a £1.17 million investment, the ROI is 4.7 years, and profits are expected to exceed £1.3 million within the next decade. Operational equipment effectiveness (OEE) has also improved significantly, rising from 17% to 55%.

This study highlights the environmental and ethical issues of nickel and cobalt production, including deforestation, biodiversity loss, pollution, and social challenges like labour exploitation and unsafe conditions. It advocates for sustainable mining practices, ethical labour standards, and responsible sourcing to align technological advancements with ethical resource management.

Optimising screening processes and adopting sustainable practices enhance efficiency, reduce waste, and meet the growing demand for high-performance materials. This study offers a roadmap for balancing industrial innovation with environmental and social accountability.

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List of Abbreviations

Abbreviation	Explanation
µm	Micron
3D	3 Dimensional
a.m.	Before Midday
ALARP	As Low as Reasonably Practicable
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
ATEX	Atmosphere Explosible
BSI	British Standards Institution
CapEx	Capital Expenditure
CEO	Chief Executive Officer
CFD	Computational Fluid Dynamics
DMAIC	Define Measure Analyse Improve Control
DOE	Design of Experiment
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
e.g.	For Example
EN	European Standard
FMEA	Failure Mode and Effect Analysis
Gs	Acceleration That Describes the Force of Gravity
HMI	Human Machine Interface
Hz	Hertz
K	Thousand (when reference to money or tonnage)
kg	Kilogram
Kg/hr	Kilogram per hour
KPI	Key Performance Indicator
kW	Kilowatt
kWh	Kilowatt-hour
LIW	Loss In Weight
MOC	Management of Change
MSDS	Material Safety Data Sheet
NGO	Non-Government Organisation
O/S	Oversize
OEE	Overall Equipment Effectiveness
OpEx	Operational Expenditure
OTIF	On Time in Full
PCL	Product Colmonoy
PLC	Programmable Logic Controller
PPE	Personal Protective Equipment
PSD	Particle Size Distribution
RAMS	Risk Assessment and Method Statement
RFT	Right First Time
RMI	Responsible Minerals Initiative
ROI	Return on Investment
RPM	Revolutions Per Minute
RPN	Risk Priority Number
S/S	Stainless Steel
SHE	Safety, Health, Environmental
SOP	Standard Operating Procedure

SoW	Statement of Work
SWI	Standard Work Instruction
UK	United Kingdom
UKCA	UK Conformity Assessed
WCL	Wall Colmonoy Limited
YTD	Year To Date

Aims and Objectives

This project aims to deliver several key objectives to improve the screening of metal powder at Wall Colmonoy, to ultimately increase profitability in the business.

The biggest aim is to reduce waste from the screening process which will improve yields through the process. These improvements will allow decreases in melt quantity allowing consumption savings and increased manufacturing capabilities.

By optimising the process to improve the overall equipment efficiency (OEE) it will allow for an escalation in right first time (RFT) rates and increase throughput times to further develop process capability and reduce inventory.

Introduction

Nickel and cobalt-based alloys are essential to modern engineering, driving innovation in aerospace, automotive, and additive manufacturing industries. Renowned for exceptional mechanical strength, unmatched corrosion resistance, and superior thermal stability, these alloys are indispensable for applications that demand extraordinary material performance. Achieving the exacting specifications for these alloys requires rigorous control across all stages of manufacturing, with particular emphasis on the management of particle size distribution (PSD) during powder production. Screening technologies are critical in this context, ensuring consistency and quality to meet the stringent demands of high performance applications.

The production of these metal powders involves a series of highly interdependent processes, starting with precise charge formulation and progressing through atomisation, screening, blending, and finally packing. Screening, in particular, is pivotal as it directly influences throughput, yield, and right-first time (RFT) quality. The rising demand for ultra-fine powders, especially those below 20 microns, for advanced applications like additive manufacturing and thermal spraying, underscores the necessity of innovative and efficient screening solutions. However, traditional screening technologies face several limitations. Rotary screening, although effective for high throughput, struggles with mesh blinding when processing ultra-fine particles. Vibratory screening, enhanced by ultrasonic technology, offers unparalleled precision but encounters scalability challenges in large-scale industrial operations. Similarly, air classification excels in achieving narrow PSDs through aerodynamic precision but suffers diminished efficiency when processing the coarse particle sizes, limiting its broader applicability in advanced manufacturing contexts.

This research seeks to address these limitations by conducting a systematic, data-driven evaluation of critical screening technologies. It evaluates the comparative performance of rotary screening, vibratory screening, and air classification, focusing on key metrics such as efficiency, yield, and PSD precision. The primary goal is to identify a screening solution that achieves an optimal balance between operational efficiency and the exacting quality standards demanded by advanced industries. Through a comprehensive understanding of these technologies, this study aims to enhance the adaptability to the evolving requirements of modern manufacturing processes.

Beyond the technical optimisation of screening technologies, this research explores the broader ethical and environmental challenges associated with nickel and cobalt production. The extraction and refinement of these metals impose significant environmental burdens, including deforestation, biodiversity loss, water contamination, and substantial carbon emissions. Additionally, social issues such as labour exploitation, unsafe working conditions, and the displacement of local communities, exacerbate the challenges of ethical production. These realities underscore the urgent need for sustainable and socially responsible practices. By integrating advanced screening technologies with a commitment to ethical resource management, this research aspires to develop a holistic production framework that aligns technological innovation with sustainability principles.

The significance of this study extends beyond its technological contributions, encompassing a strong emphasis on global sustainability objectives. The integration of advanced screening methods has the potential to reduce material waste, enhance energy efficiency, and improve overall productivity. Simultaneously, the adoption of ethical and environmentally conscious practices ensures alignment with international sustainability initiatives. For instance, hybrid screening approaches, such as combining vibratory screening with air classification, can effectively address the limitations of individual technologies while enhancing throughput, yield, and PSD precision. This dual focus on operational performance and sustainability ensures the viability of manufacturing processes in an increasingly resource conscious world.

Ultimately, this research is positioned at the intersection of technological innovation and sustainability, addressing both operational and ethical dimensions of alloy production. It seeks to optimise screening processes to enhance manufacturing efficiency while minimising the ecological and social impacts of metal powder production. The findings aim to provide actionable insights for manufacturers, enabling them to meet the escalating demand for high performance materials while adhering to rigorous environmental and ethical standards. This comprehensive approach situates the study as a critical contribution to the evolving field of alloy production, balancing the imperatives of innovation, accountability, and long-term sustainability.

1. Background of Wall Colmonoy

Wall Colmonoy traces its origins back to 1937 when Norman Cole and Walter Edmonds developed a nickel-based alloy, known for its high hardness and exceptional resistance to wear and corrosion. This alloy, named "Colmonoy," led to the establishment of Wall Colmonoy Corporation in Detroit, Michigan, by A. F. Wall in 1938.

In 1969, the company's European headquarters were relocated from Brackley, UK, to Pontardawe, Wales, under the leadership of Group Chairman W. P. Clark Sr. The 1990s saw significant product developments with the introduction of the Colmonoy '200' and '88' series for the oil and gas sectors in 1991. By 1999, the company expanded its operations to a facility in New Mexico, which focused on atomisation processes, along with a modest expansion of the UK headquarters. The growing demand necessitated a major expansion of the UK plant in 2005, increasing its capacity by 25%.

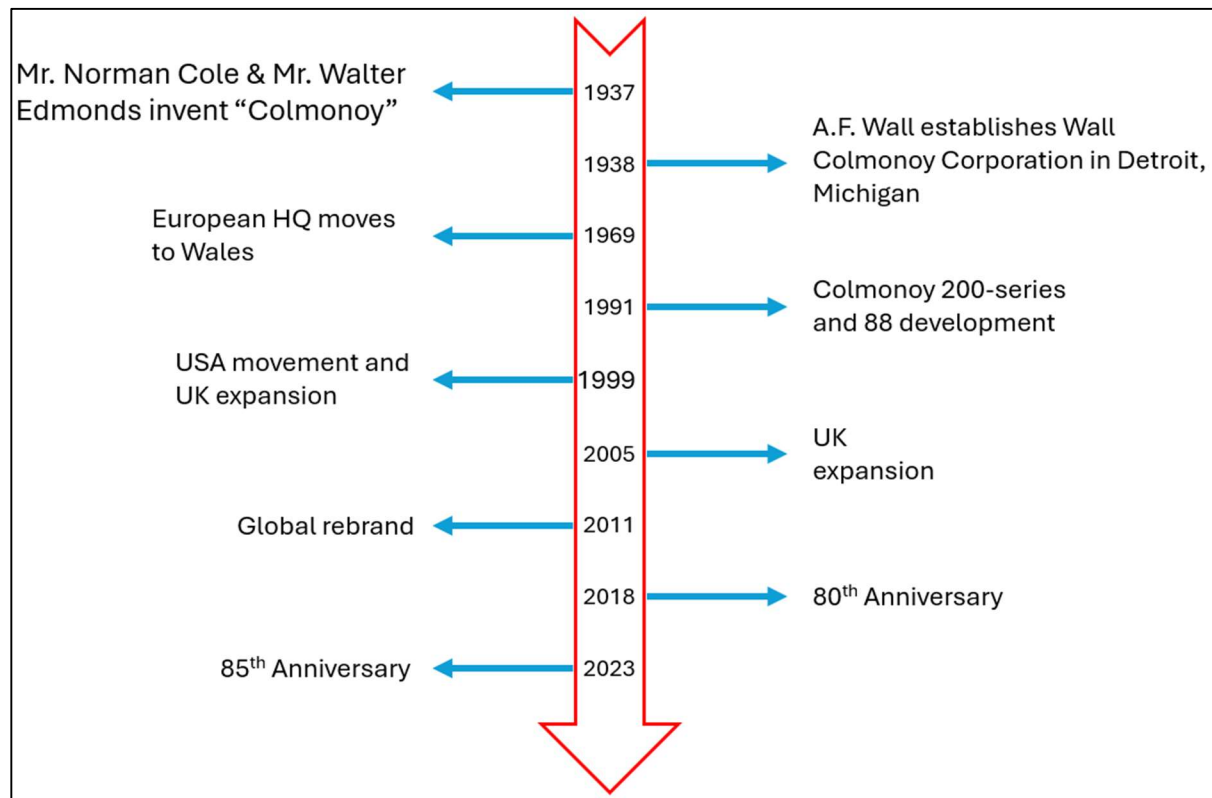


Figure 1 – Wall Colmonoy Timeline

In 2011, Wall Colmonoy underwent a comprehensive global rebrand, reflecting a refreshed position, visual identity, and communication strategy aimed at supporting long-term growth, as outlined in figure 1. Celebrating its 80th anniversary in 2018, Wall Colmonoy continues to serve a diverse range of industries including aerospace, automotive, glass, oil and gas, and mining. The organisation then went on to celebrate its 85th anniversary which was celebrated globally highlighting the achievements made throughout the decades.

The focus of this research is on various screening technologies, chosen due to the trials being conducted at Wall Colmonoy, a manufacturer specialising in nickel and cobalt alloys, that employ multiple screening methods for various product lines. With a rich history and significant presence in the metallurgy sector, Wall Colmonoy's European headquarters in South Wales have established a reputation for producing high-performance alloys for hard surfacing and other industrial applications.

2. Literature Review

The purpose of this literature review is to provide a comprehensive analysis of existing research and methodologies relevant to the optimisation of screening technologies in the production of nickel and cobalt-based alloys. It explores the theoretical underpinnings and practical applications of screening technology highlighting the respective strengths, limitations, and areas for improvement. Additionally, this section examines the broader environmental and ethical implications of alloy production, situating these technologies within the context of sustainable and socially responsible manufacturing practices. By synthesising the current body of knowledge, this review establishes a foundation for the research and identifies gaps that this study seeks to address.

2.1. Process of Making Metal Powder

The manufacturing process of nickel and cobalt-based alloys comprises several critical steps, each vital to ensuring the overall quality and properties of the final product. Initially, the process begins with charge formulation, where precise proportions of raw materials, including nickel, cobalt, and additional alloying elements, are meticulously calculated and mixed (Yule & Dunkley, 1994).

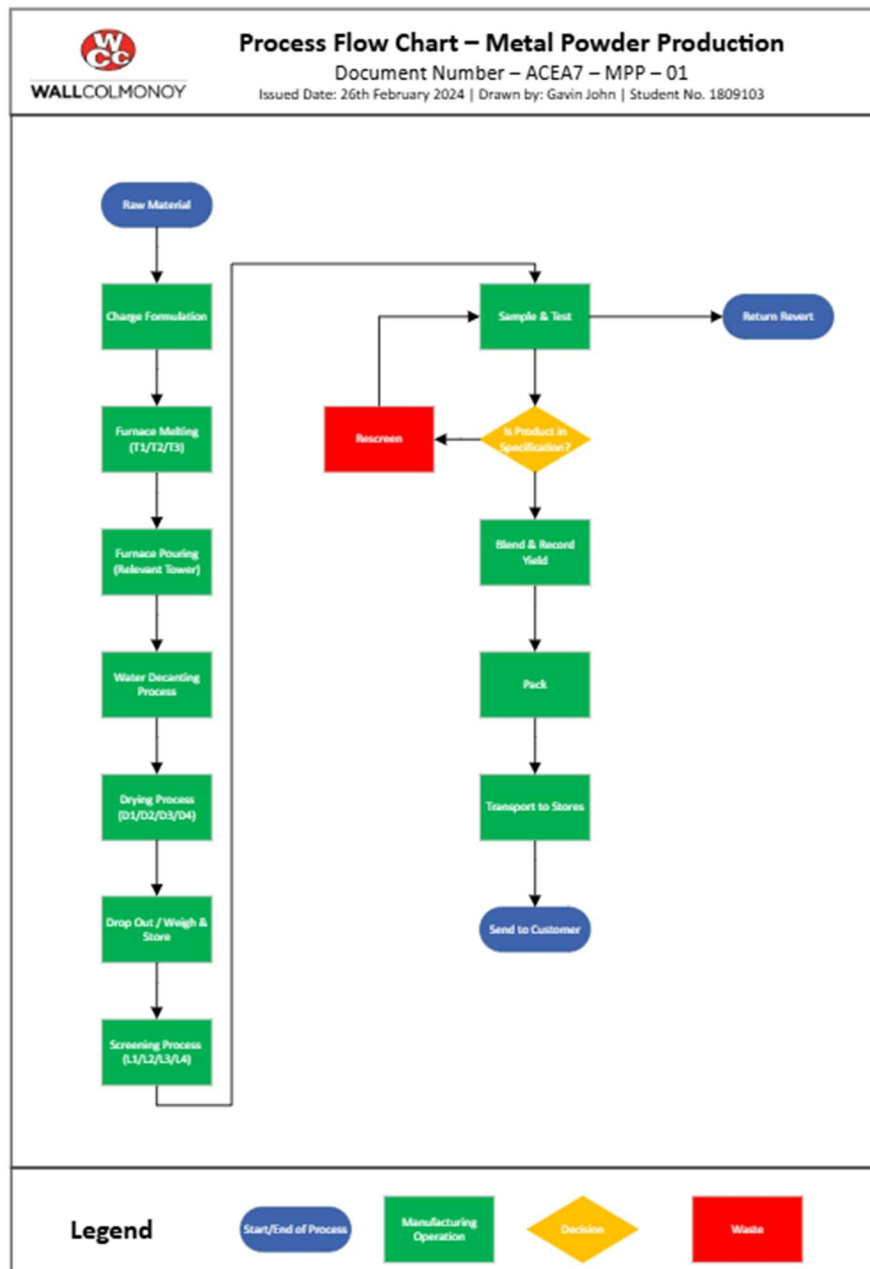


Figure 2 - WCL Flow Diagram

Figure 2 gives an outline picture of the process steps for the manufacture of alloys at WCL. The atomisation process consists of manufacturing and drying the powder ready for screening. This is then screened until the specification is met where the waste material goes back to revert, and the finished product is packed and sent to the customer.

Subsequently, the mixture undergoes atomisation, a process in which the molten metal is rapidly cooled and solidified into fine powder particles by a high-velocity gas or liquid stream, as shown in figure 3. This results in a powder that is then subjected to drying to eliminate any residual moisture, thereby ensuring the material's integrity and consistency (Dunkley, 2002).

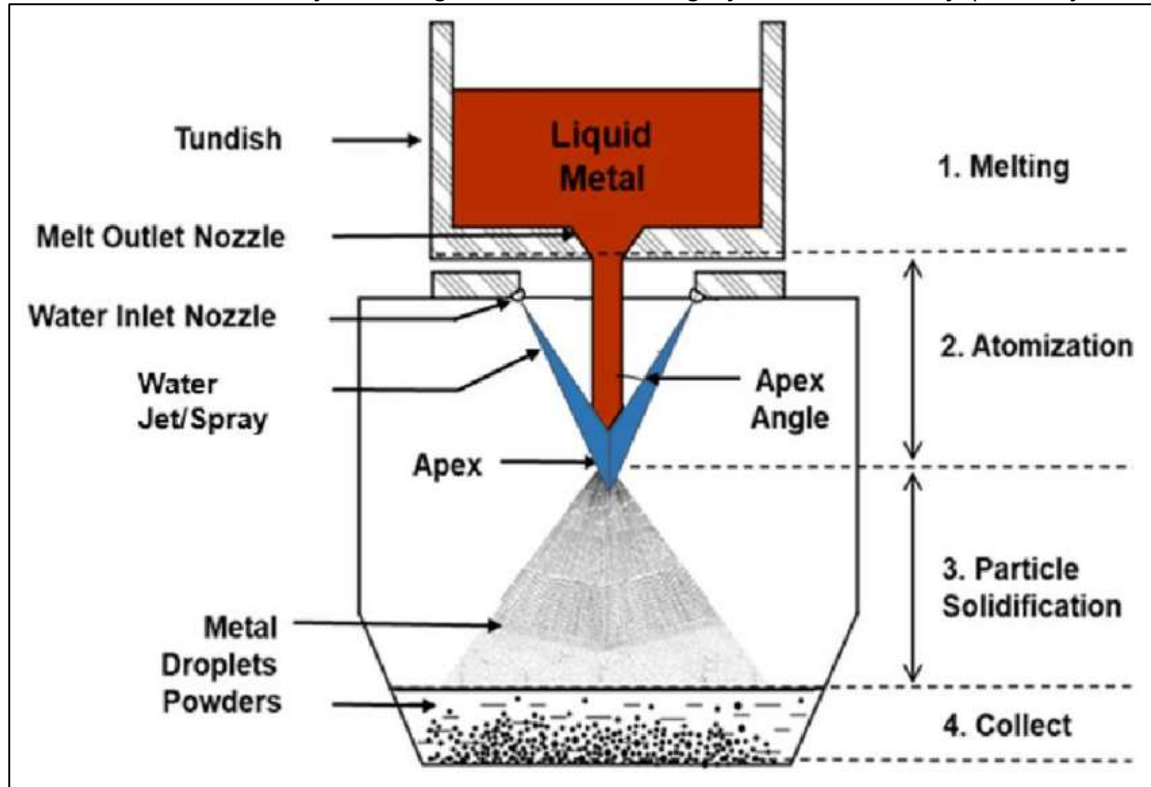


Figure 3 – Atomising Overview (Asgrian, et al., 2018)

Once dried, the powder is screened to achieve the desired particle size distribution, a crucial step for attaining uniformity in the final alloy (Dao, et al., 2022), as shown in figure 4. The screened powders are then blended to ensure homogeneity, involving the mixing of different batches to balance any slight variations in composition.

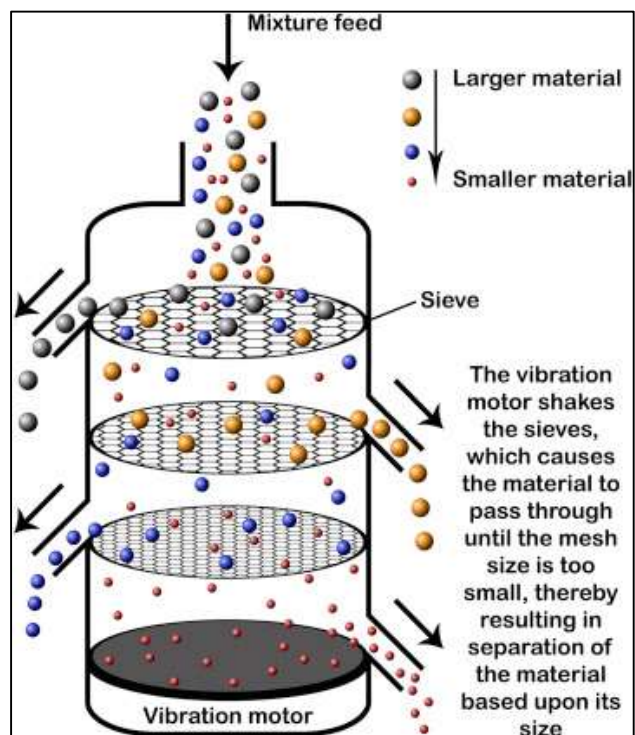


Figure 4 - Overview on how screening works (Morrison,

The final step involves packing the blended powder in a controlled environment to prevent contamination and preserve its quality, making it ready for further processing or direct application (Schade, 2015). Figure 5 shows the packing machine at WCL where the material is fed into the top hopper and utilises a scale and foot press to allow accurate packing into 5kg bottles. Throughout this process, each step is meticulously monitored and optimised to produce high-performance nickel and cobalt-based alloys, which are essential for various high-tech and industrial applications.



Figure 5 – Packing Machine (Autopack, 2024)

In addition to the manufacturing steps, rigorous quality control and testing procedures are implemented to ensure the alloys meet stringent industry standards. These procedures include chemical analysis, particle size distribution assessment, and mechanical testing to verify the alloys' properties. Figure 6 gives an example of the element tester at WCL, where this test gives an accurate results within a 5 minute period. Consistent quality control measures guarantee that the alloys exhibit the desired hardness, wear resistance, and corrosion resistance, thereby maintaining their suitability for critical applications (Neikov, et al., 2009).



Figure 6 – Chemical Element Tester (LECO, 2024)

2.2. Screening Technologies Available for Metal Powder

Various screening technologies are employed to screen metal-based alloys, particularly those composed of nickel and cobalt. The first method is vibrating sieving, which utilises a series of vibrating screens made of wire mesh to separate particles based on size (Makinde, et al., 2015), figure 7 gives an example of this. The vibrating motion facilitates the separation process by allowing particles to pass through screens of varying mesh sizes, where (Bilal, 2015) claims one company to be over 99% efficient down to $7\mu\text{m}$.

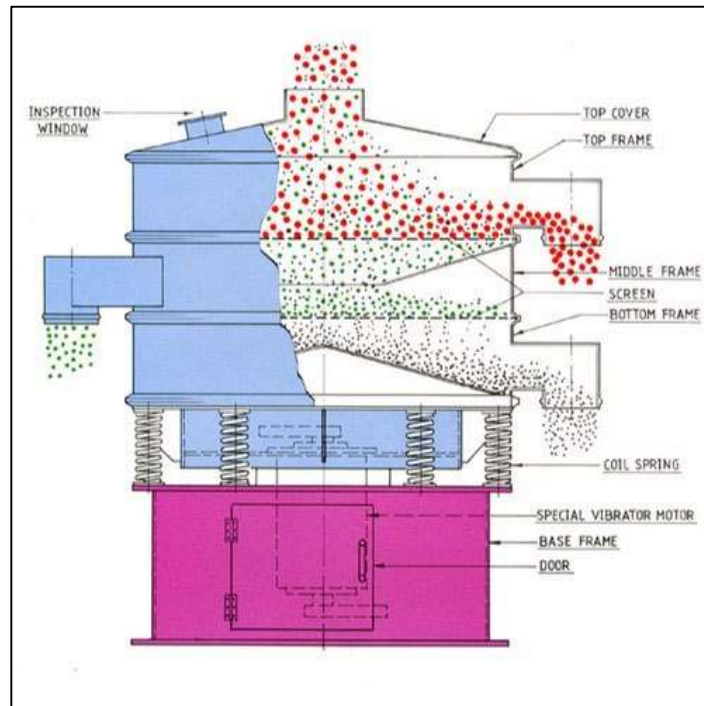


Figure 7 - Schematic of Screening Metal Powder (Singh, 2013)

Ultrasonic sieving offers an alternative with similar properties. This technology operates on the principle of using high-frequency vibrations to separate particles into size-specific fractions (Bebbington & Allen, 2003). A third option is air classification, which relies on air to separate particles based on morphology. The classifier works by blowing air through a nozzle into a chamber filled with particles, creating split fractions through mesh (Neikov, et al., 2009). Rotary sieving is another method where particles are placed in a rotating drum, and centrifugal forces push finer particles through a perforated mesh (Neikov, et al., 2009). The final option is the centrifugal sifter, which uses a spinning rotor to force material through a series of meshed screens, utilising centrifugal force to achieve size separation (ANGELO, et al., 2022). Each of these technologies are advantageous for specific applications. However, with the advent of additive manufacturing, there is an increasing demand for ultra-fine metal powders (below 20 microns). This requirement poses challenges for most of the aforementioned technologies. Vibratory sieving stands out as a viable solution, as it is claimed to achieve particle sizes as fine as 7 microns, meeting the needs of modern manufacturing requirements.

2.3. Rotary Screening

Rotary screening is a widely used method for separating and classifying particles based on size and morphology. This technique operates on the principle of rotation around a horizontal axis, utilising a drum equipped with a series of perforated slots to separate particles into distinct size fractions (Pankratz, 2017). A schematic representation of rotary screening is depicted in figure 8. In this process, particles smaller than the aperture pass through the mesh, while larger particles remain on the mesh and are conveyed to an outlet as the drum rotates.

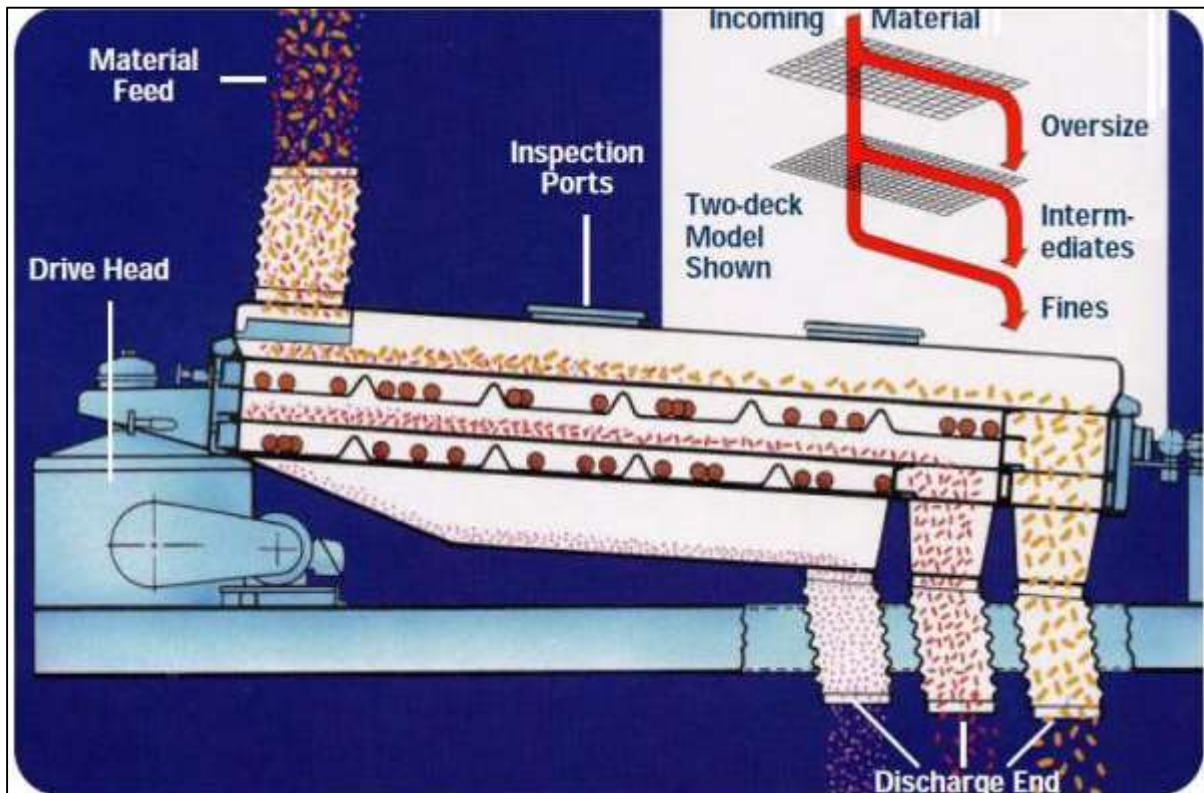


Figure 8 - Rotary Screening Schematic, Courtesy of (Arcon, 2013)

The drum is powered by a motor and a drive mechanism, which can be coupled with an inverter to allow for variable speed control. The motor generates a rotational force that is transmitted to the drum, causing the particles to move and undergo separation. This method is not only applicable to the metal powder industry but also finds utility in various other sectors, including agriculture, food processing, and pharmaceuticals, among others (Upadhyaya, 1997).

2.3.1. Advantages of Rotary Screening

Rotary screening methods offer numerous advantages, making this process highly suitable for industrial applications. These methods are known for high efficiency, cost-effectiveness, and low maintenance requirements. Rotary screeners are particularly adept at handling large volumes of material and can operate at high speeds, which is essential for industrial-scale manufacturing. The precision of rotary screeners is notable, as they can accurately classify particles down to a 53-micron size (Rotex, 2023), ensuring a high level of accuracy in particle separation and classification.

2.3.2. Limitations of Rotary Screening

Despite its numerous advantages, rotary screening has some limitations that need to be considered. One significant limitation is the tendency for blinding and pegging of the mesh, where particles that are near or the same size as the mesh aperture become wedged in the openings, impeding efficient screening (Ferris, 1998). Additionally, rotary screeners are more suited to larger particles, and efficiency diminishes when screening finer grades. This reduction in efficiency can be a critical drawback in applications requiring the separation of ultra-fine particles.

2.4. Vibratory Screening

Vibratory screening is a widely utilised technique for separating and classifying particles based on shape and size. This method operates on the principle of vibration, where particles are subjected to mechanical vibrations that facilitate movement and separation, as illustrated in figure 9. The mechanical components of vibratory screeners are similar to those of other screening devices, with a motor driving a mechanism to generate vibrations. However, in vibratory screening the vibrations pass through a horizontal plane, allowing for the achievement of higher frequencies. This screening method is prevalent in manufacturing industries and is particularly effective in industries dealing with finer particles (M. Cherkasova, 2019). Vibratory screeners are favoured for its superior efficiency in achieving cut points below 53 microns them it is more suitable than rotary screeners for applications requiring fine particle separation.



Figure 9 - Vibratory Screening Schematic, Courtesy of, (Kay, 2010)

2.4.1. Advantages of Vibratory Screening

Advancements in vibratory screening technology have led to the development of debinding technologies that extend the lifespan of the mesh used in these screens. One significant innovation is the incorporation of ultrasonic sieves, which introduce additional high-frequency vibrations through the mesh. These vibrations help dislodge particles that may become wedged in the mesh apertures, enhancing the efficiency of the screening process (Yan, et al., 2020). The screens used in these systems are designed to be lightweight, and apparatuses have been developed to allow for single-person operation during screen changes, thus increasing productivity and minimising downtime.

Furthermore, the construction of modern vibratory screeners includes effective dust containment features, with ventilation ports designed to limit dust exposure to the atmosphere. This is particularly important for maintaining a clean and safe working environment. Similar to rotary screening, vibratory screeners now feature advanced controls that have been refined over the years. These controls allow for better management of throughput and optimisation of performance, making vibratory screening a highly efficient and adaptable technology for various industrial applications.

2.4.2. Limitations of Vibratory Screening

Despite its many advantages, vibratory screening technology has certain limitations. One primary drawback is its limited scalability for larger production volumes, as these screening units are compact and constrained in their processing throughput. This limitation can make it challenging to meet higher production demands, particularly in large-scale industrial applications (Gibbons, et al., 2024).

2.5. Air Classification

Air classification is a critical process in the production of metal powders, including those used in high-performance nickel and cobalt-based alloys. It involves the separation of powder particles based on size and density by using a stream of air to classify the particles into different size fractions. This technique is essential for ensuring the quality and consistency of metal powders, which directly impacts the performance of the final alloy products. Air classification leverages the aerodynamic properties of particles to achieve size segregation. According to Rhodes (2008), the process involves feeding the powder into an air stream, where centrifugal and gravitational forces act on the particles. Smaller and lighter particles are carried with the air stream, while larger and denser particles fall out of the flow. The efficiency of air classification is influenced by factors such as particle size distribution, shape, density, and the velocity of the air stream (Kelly & Spottiswood, 1982). An example of how an air classifier separates particles is shown in figure 10.

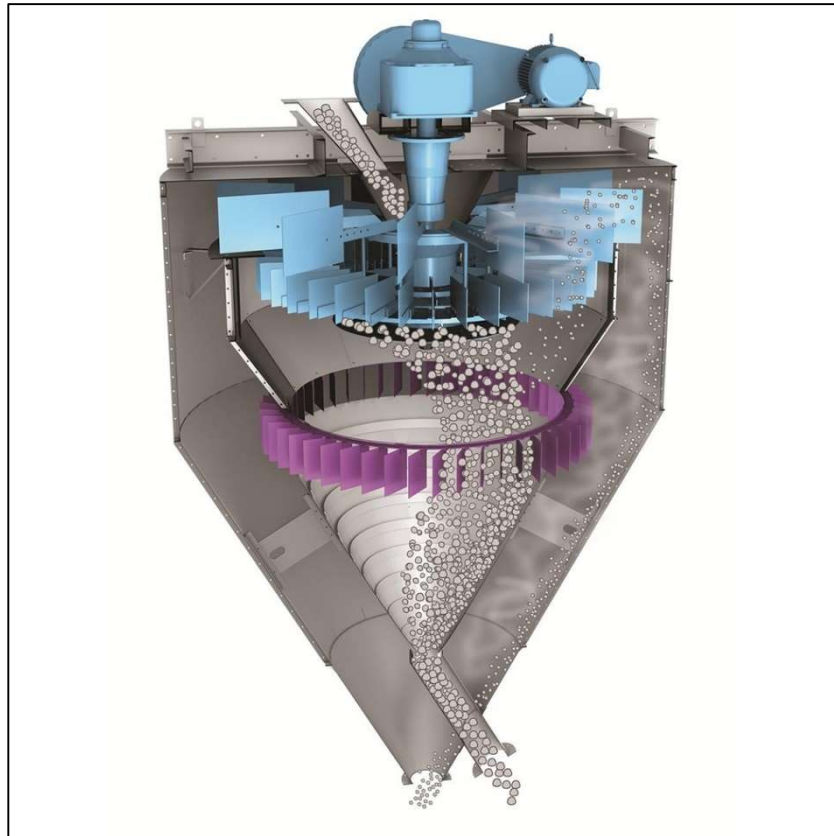


Figure 10 – Air Classification Schematic, Courtesy of (Energy, 2024)

2.5.1. Advancements in Air Classification Technology

Recent advancements in air classification technology have focused on improving the precision and efficiency of particle separation. Modern classifiers, such as the centrifugal air classifier, utilise a rotating wheel to enhance particle separation. (Zhou, et al., 2016) it's been highlighted that innovations in classifier design, including the use of high-speed rotors and adjustable classifier wheels, have significantly improved the cut size accuracy and throughput of air classifiers.

Another notable development is the integration of computational fluid dynamics (CFD) in the design and optimisation of air classifiers. CFD simulations allow for detailed analysis of the airflow patterns and particle trajectories within the classifier, enabling engineers to fine-tune the design for optimal performance (Wang, et al., 2018) an example is shown in figure 11.

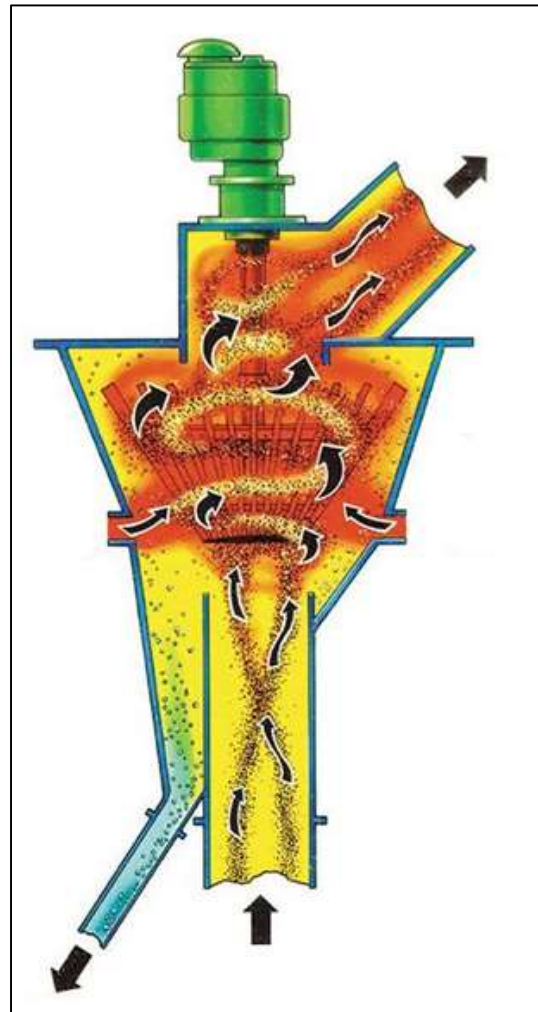


Figure 11 – Example of CFD Analysis on Air Classifier (Metso, 2024)

2.5.2. Applications of Air Classification in Metal Powder Processing

Air classification is widely used in the production of metal powders for various applications including, additive manufacturing, powder metallurgy, and thermal spraying. In the context of additive manufacturing, precise control over particle size distribution is crucial for achieving consistent layer deposition, and mechanical properties in the printed parts (Gibson, et al., 2015). Air classification ensures that the metal powders used in these processes have a narrow particle size distribution, which is essential for maintaining the flowability and packing density of the powder.

In powder metallurgy, air classification helps in producing powders with the desired particle size range, which influences the sintering behaviour and final properties of the sintered parts. For thermal spraying applications, the uniformity of particle size achieved through air classification ensures consistent coating, thickness, and quality (Liu & Shi, 2012).

2.5.3. Challenges and Future Directions

Despite its advantages, air classification faces challenges, such as the handling of ultra-fine particles and the classification of particles with similar aerodynamic properties. Ongoing research aims to address these challenges through the development of more sophisticated classifiers, and the use of advanced materials for classifier components to reduce wear and improve efficiency (Burt, 2019).

Future research directions include the exploration of hybrid classification techniques that combine air classification with other separation methods, such as sieving or magnetic separation, to enhance the overall classification performance. Additionally, the integration of real-time monitoring and control systems in air classifiers could lead to more adaptive and automated processes, further improving the quality of metal powders.

2.6. Factors Affecting Screening

This section examines the critical factors influencing the performance and efficiency of screening technologies in the production of nickel and cobalt-based alloys. The discussion focuses on the interplay between particle morphology, feed rate, screen aperture size, and operational parameters, which collectively determine the effectiveness of particle separation and throughput. By exploring these variables, this section aims to elucidate the technical and operational challenges inherent in screening processes and to identify opportunities for optimisation. The insights presented serve as a foundation for developing tailored solutions that address both the technical limitations and the evolving demands of advanced manufacturing industries.

2.6.1. Morphology

Morphology refers to the shape of powder particles, which can range from highly spherical to agglomerated forms, as illustrated in figure 12. Ideally, particles would be uniformly spherical, but variations in the atomising process often produce a range of shapes, including irregular or elongated forms. These non-spherical particles, particularly elongated shapes known as "needles," can disrupt screening processes by introducing lower-quality particles into the product, leading to potential blockages and processing issues for end users (Beckers, et al., 2020), an example is highlighted in the image below.

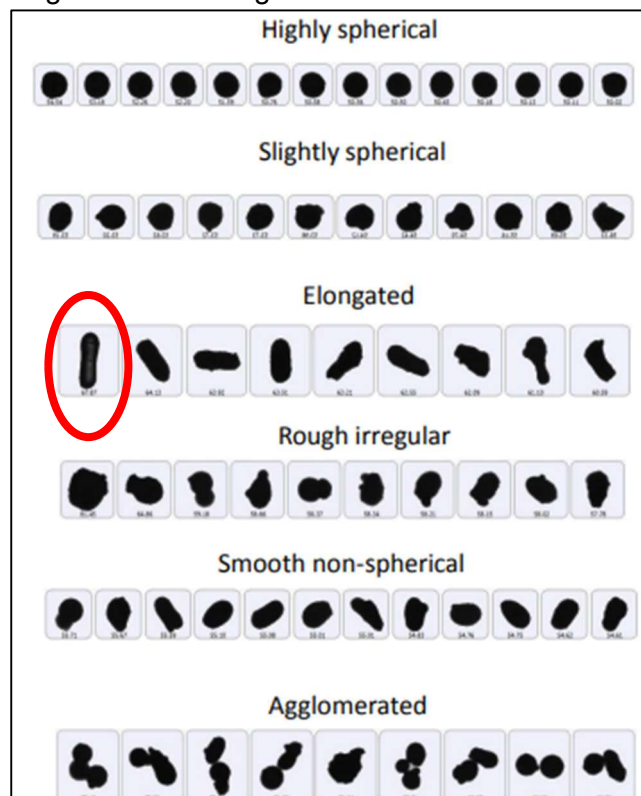


Figure 12 - Morphology Classifications Examples, Courtesy of (Colmonoy, 2022)

Beyond morphology, several operational factors affect screening efficiency, including the screen's aperture size and the material feed rate. The screen aperture, which is often specific to the product being processed, must be carefully selected and maintained. Variability in screen manufacturing can impact aperture accuracy, making it essential to regularly inspect screen sizes upon delivery and throughout the operational lifespan.

Another critical factor is the feed rate which is the speed at which material is introduced onto the screen. An excessively high feed rate risks damaging the screen's central area, while an overly slow rate can reduce throughput efficiency. Achieving an optimal balance in feed rate is therefore crucial for effective screening performance, as it ensures both the durability of the screen and the productivity of the process.

2.6.2. Solidification

Unlike pure metals, which typically solidify at a distinct temperature, alloys solidify over a temperature range. Solidification begins at the liquidus point, where the material transitions from a solid to a molten state. The phase at which the molten material fully solidifies is known as the solidus, with the intervening temperature range referred to as the pasty or slushy region (Wang, et al., 2020). As shown in the example in figure 13, this was performed on one of the product lines at WCL, which shows a solidus liquidous temperature around 1,340°C.

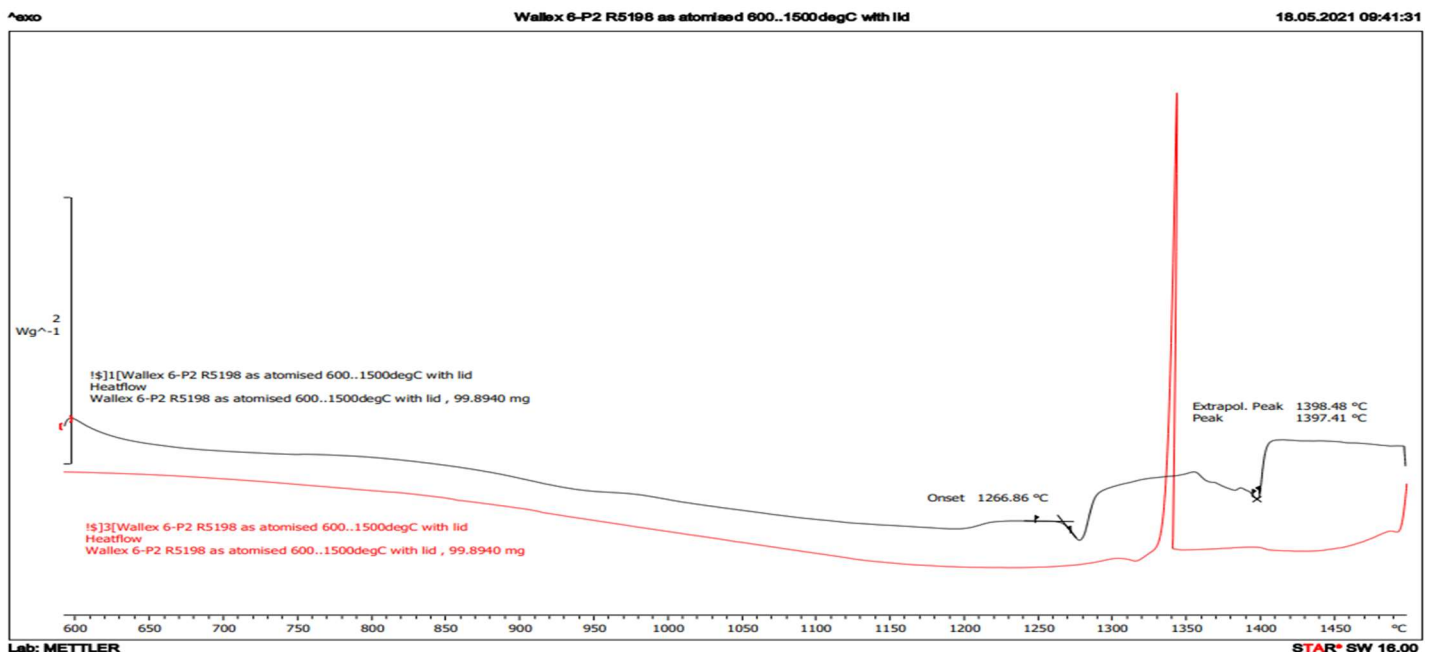


Figure 13 - Solidification graph

In eutectic alloys, both the liquidus and solidus converge at a specific point known as the eutectic point, allowing for solidification at a single temperature. A cooling curve can be used to measure the rate of solidification over time. During the liquid phase, the atoms or molecules are randomly oriented, while in the solid state, they organise into a fixed, patterned structure, often forming a crystal lattice. During solidification, these regular patterns create crystalline structures as the metal cools, with atoms arranging into dendritic formations. As these dendrites grow, molten metal may become entrapped within the branches, remaining in a liquid state until the full solidification temperature is achieved (Chandra, et al., 2024).

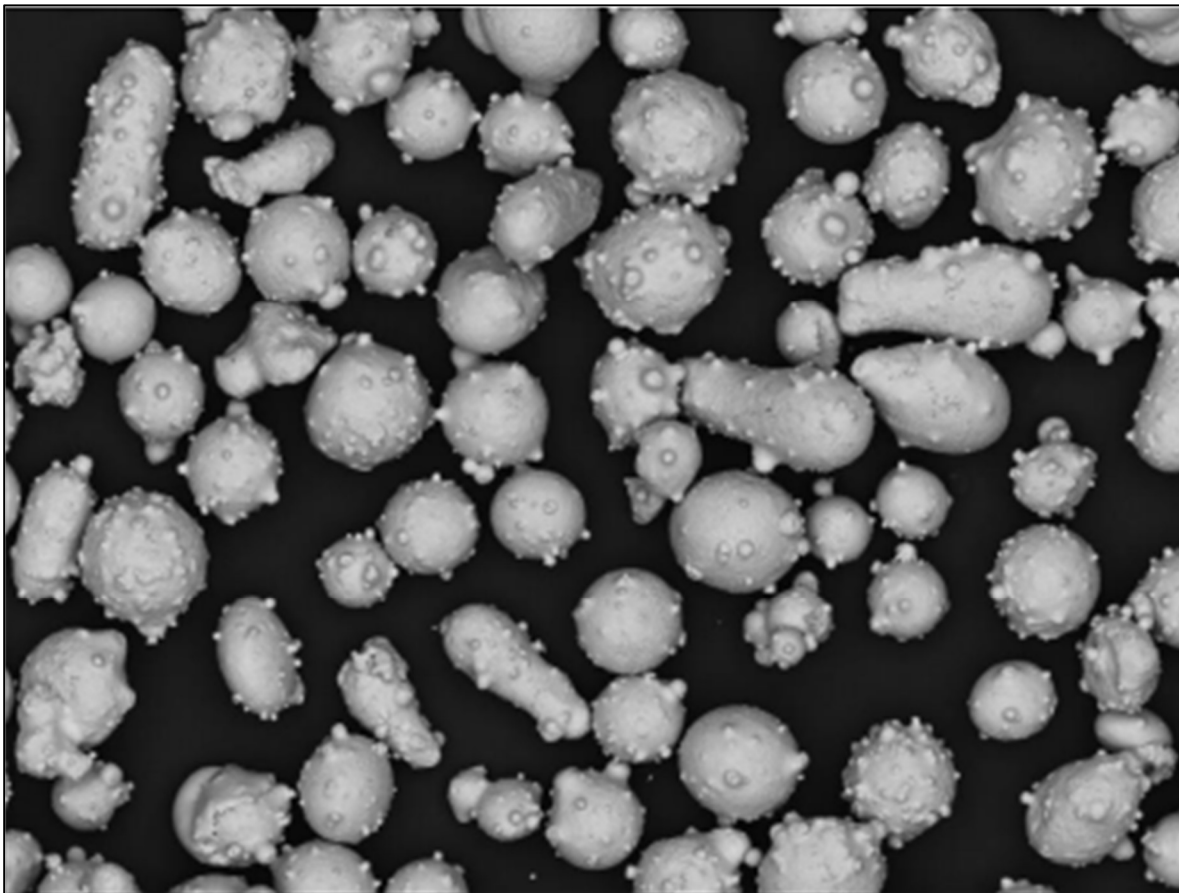


Figure 14 - Morphology of Powder at WCL

Compared to pure metals, alloys exhibit a more complex solidification process due to the absence of a single freezing point, instead undergoing a transition across a range of temperatures. Alloys with an extended freezing range have a substantial gap between the solidus and liquidus temperatures, creating a slushy or partially solidified zone. This stage allows particles to adhere to each other and to nearby surfaces, as illustrated in figure 14. This is problematic for screening as these types of particles can cause screen blinding which decreases the overall screening performance.

2.6.3. Particle Size Distribution

Particle size distribution (PSD) significantly influences the solidification rate of an alloy. Larger particles require more energy to cool, resulting in a slower cooling rate. The atomisation process produces a diverse range of particle sizes within each batch, and a bell curve on a logarithmic scale can represent the PSD of these particles. An example of this is shown in figure 15 where there is a wide range between 296 micron and -6micron.

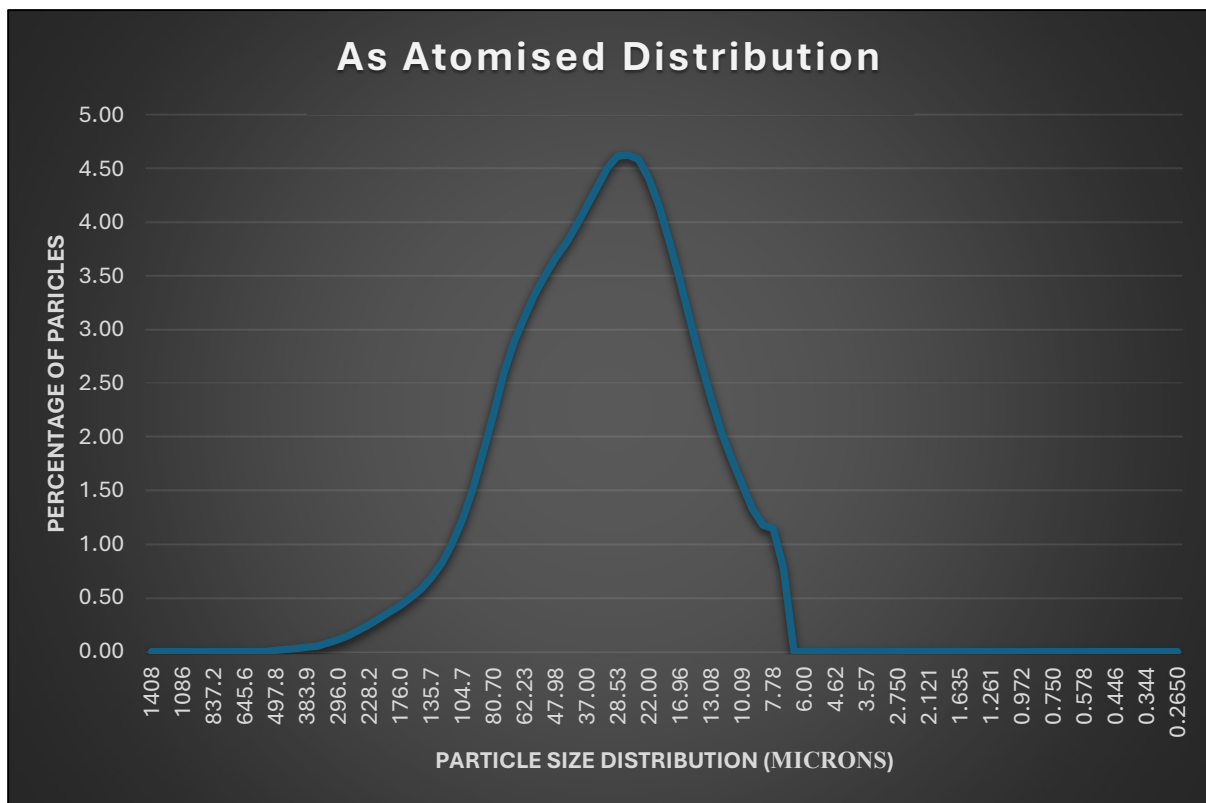


Figure 15 – As Atomised PSD Graph of Powder Being Used

Due to the prolonged cooling times associated with larger particles, oxidation can develop on the outer surfaces. Lower d50 (median) values correspond to finer particle sizes, reducing the likelihood of oxidation compared to batches with higher d50 values. To assess particle sizes and determine d50 values, a laser diffraction analyser is employed to generate precise PSD data. This equipment, actively used by WCL for quality control across all products, is depicted in figure 16.



Figure 16 – Laser Diffraction Analyser at Wall Colmonoy

2.7. Ethical Implications of Nickel

Nickel is an essential component in the manufacture of various high-performance alloys, particularly those used in the aerospace, automotive, and electronics industries. However, the extraction, processing, and use of nickel raise several ethical concerns that warrant attention. This section examines the environmental, social, economic, and labour-related impacts associated with nickel production, emphasising the importance of sustainable practices and ethical considerations in the manufacturing process. From figure 17, below there is a high degree of water pollution due to the mining of Nickel. Another notable fraction is the environmental impacts which relate to the mining operations along with handling Nickel.

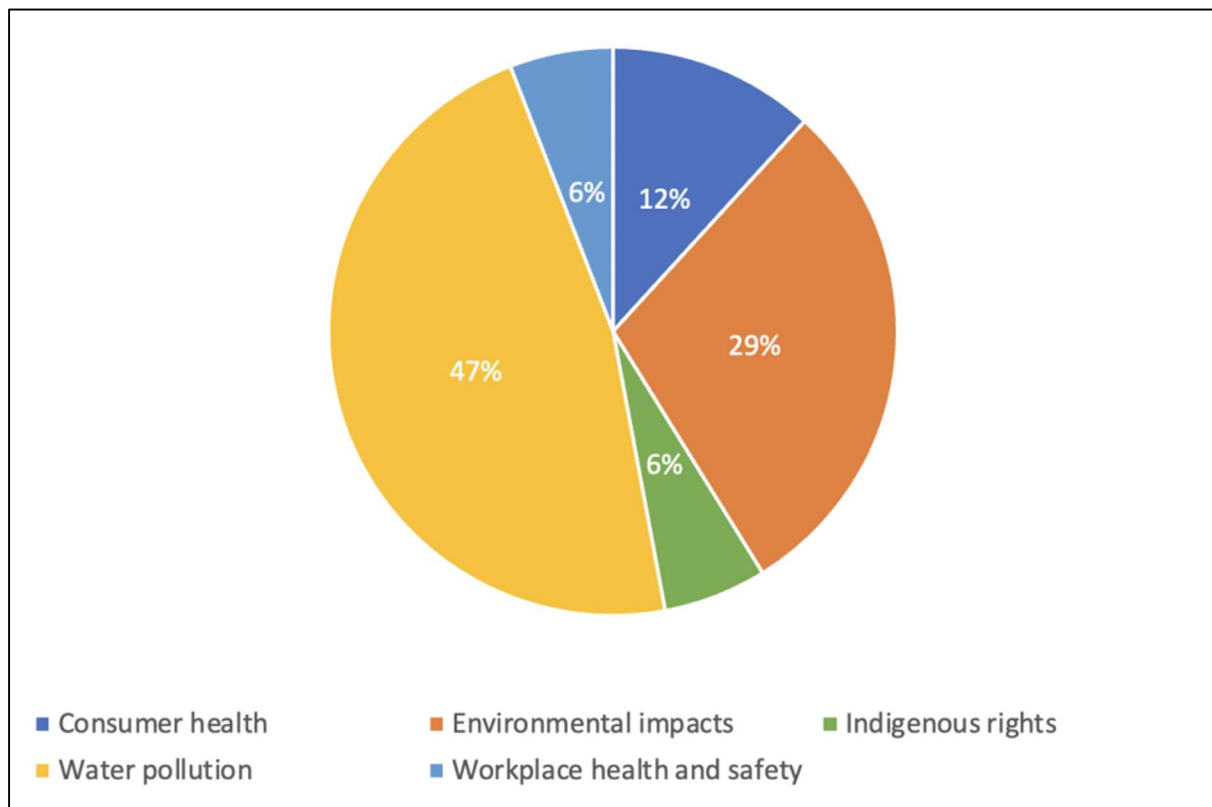


Figure 17 – Implication of Nickel Graph, Courtesy of (Sebrell, 2023)

2.7.1. Environmental Impact

The extraction of nickel, predominantly through open-pit and underground mining, presents substantial environmental challenges. These mining techniques disrupt extensive areas of land, leading to deforestation, biodiversity loss, and soil erosion. Additionally, the extraction process generates large quantities of waste, including tailings that may contain hazardous chemicals and heavy metals. Without proper management, these tailings have the potential to contaminate local water sources, posing risks to surrounding ecosystems and nearby communities (Mudd, 2010).

The environmental impact extends to the smelting and refining stages, where nickel ore processing releases sulphur dioxide and other pollutants, contributing to air pollution and acid rain. The energy-intensive nature of nickel production also results in a significant carbon footprint, raising ethical concerns about its long-term sustainability. With climate change becoming a pressing global issue, the carbon emissions associated with nickel production further highlight the need for sustainable practices within the industry (Norgate & Jahanshahi, 2010).

2.7.2. Social Impact

Nickel mining frequently takes place in regions inhabited by vulnerable populations, leading to a range of social challenges. Mining operations have, in some instances, been linked to the displacement of indigenous communities, loss of traditional livelihoods, and violations of land rights. The presence of intensive mining activities can also cause social disruptions, including higher crime rates and health issues associated with environmental pollution and inadequate working conditions (Hilson, 2002).

2.7.3. Economic Impact

The economic implications of nickel production are multifaceted. While nickel mining can substantially contribute to the economic development of resource-rich countries through job creation, revenue generation, and attracting foreign investment, these economic benefits often do not reach the local communities most directly impacted by mining activities. In some cases, profits are unevenly distributed, leading to economic inequality and social tensions (Söderholm & Svahn, 2015).

Moreover, increasing global demand for nickel is driving investment in new mining projects, which, if not managed responsibly, could exacerbate existing environmental and social challenges. Sustainable economic practices in nickel production require carefully balancing industrial demand with the rights and well-being of affected communities, ensuring that local populations benefit from mining activities without facing undue harm.

2.7.4. Labor Rights: Addressing Slave and Child Labor

A critical ethical issue within the nickel supply chain is the reported use of forced and child labour. Evidence indicates that, particularly in developing regions, children and vulnerable adults are compelled to work in nickel mines under dangerous conditions. These workers frequently endure extended hours for minimal wages, often without adequate protections for health and safety. The exploitation of forced and child labour in nickel mining represents a severe breach of human rights and raises significant ethical concerns regarding the integrity

of the supply chain as a whole (International, 2016). From figure 18 it can be seen the majority of mining takes place in Indonesia and the Philippines, total over 60%.

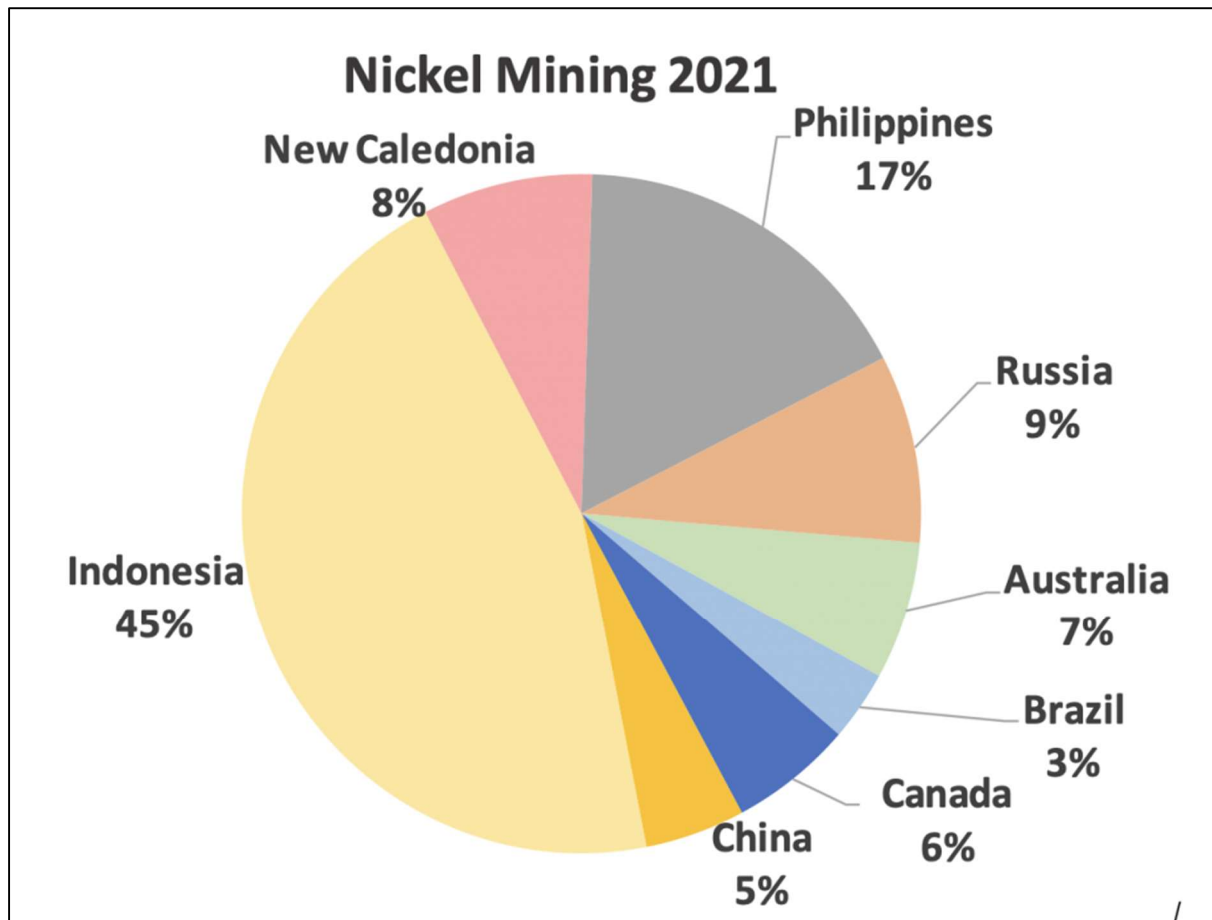


Figure 18 – Countries Where Nickel is Mined, Courtesy of (Sebrell, 2023)

2.7.4.1. Child Labor

In certain regions where nickel is mined, children are engaged in physically demanding and hazardous activities, including lifting heavy materials, operating machinery, and working in restricted spaces. Such labour places these children at substantial health risk, exposing them to respiratory issues, musculoskeletal strain, and a high likelihood of accidents. The deprivation of education and basic childhood rights for these children perpetuates poverty cycles, restricting future prospects and opportunities (Watch, 2018).

2.7.4.2. Slave Labor

Reports have highlighted instances of forced labour in the nickel mining industry, where individuals are compelled to work under threats, trapped by debt bondage, or, in extreme cases, through abduction. These workers endure harsh and inhumane conditions, often receiving little to no compensation and facing severe repercussions if they attempt to leave. The use of forced labour represents a serious human rights violation and remains an unacceptable practice across all sectors (Verité, 2017).

2.7.5. Ethical Considerations and Sustainable Practices

To mitigate the ethical impacts associated with nickel production, companies can implement a range of sustainable practices and adhere to ethical frameworks.

Environmental stewardship calls for the adoption of eco-friendly mining practices, including responsible waste reduction, proper management of tailings, and efforts to minimise habitat disruption. Investing in cleaner technologies and renewable energy sources within nickel production can further reduce environmental harm (Smith, 2013).

Social responsibility emphasises the importance of engaging constructively with local communities and respecting the rights of workers. This involves fair compensation for land use, local infrastructure investment, and equitable distribution of mining benefits. Transparent communication and inclusive decision-making are essential for building trust and fostering positive relations with communities impacted by mining activities (Kemp & Owen, 2013).

Labour rights in the nickel industry are critical, with a focus on ensuring safe working environments, fair wages, and accessible healthcare for employees. Companies should comply with international labour standards, collaborating with unions and advocacy organisations to uphold workers' rights ((ILO), 2003).

To combat slave and child labour, companies must perform comprehensive due diligence to maintain supply chains free from exploitative practices. This involves enforcing stringent supplier standards, conducting regular audits, and collaborating with local authorities and non-government organisations (NGO) to improve labour conditions. Certifications like Fairtrade and initiatives such as the Responsible Minerals Initiative (RMI) support companies in sourcing nickel ethically (OECD, 2019).

Regulatory compliance highlights the role of governments in enforcing environmental and social protections for local communities. Effective legal frameworks and monitoring systems are essential to hold companies accountable, ensuring mining practices adhere to ethical and sustainable standards (Hodge, 2014).

2.8. Representative sampling

Accurate product analysis relies on representative sampling, which is essential for obtaining precise results. The sampling process follows ASTM B215 – Sampling of Metal Powder, with key points from this standard incorporated into the operator's standard work instruction (SWI).

In the industry, the preferred method for sampling follows a 'start, middle, and end' approach. As recommended in (International, 2020), sampling should ideally be performed while the powder is in motion, as this prevents the segregation that often occurs in collection hoppers, where fine particles tend to settle on top. Figure 19 shows an example of segregation and the different range of particles built up on one another. This would provide false readings during testing, hence the need for a homogeneous mix for testing and application purposes.

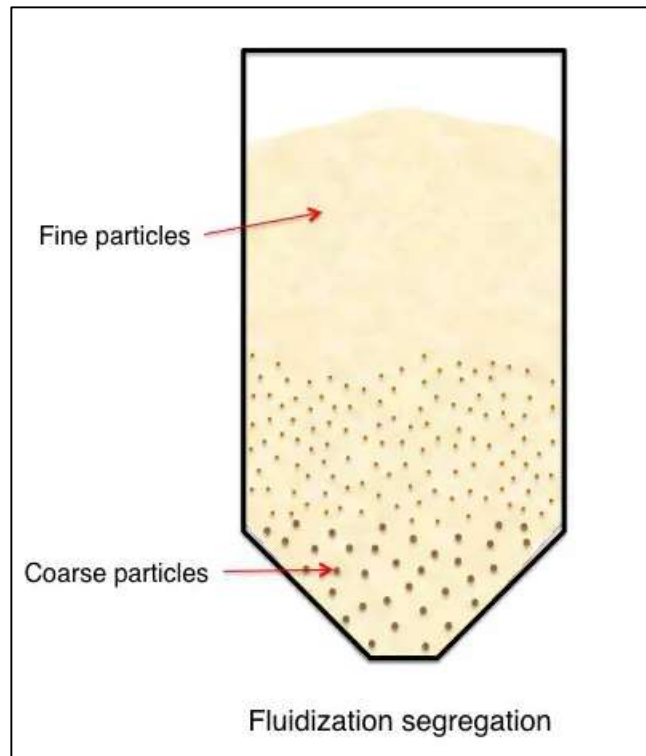


Figure 19 – Segregation (Johanson, 2024)

Figure 20 illustrates particle segregation, showing a homogenised sample on the left and two examples of particle-size-based segregation.

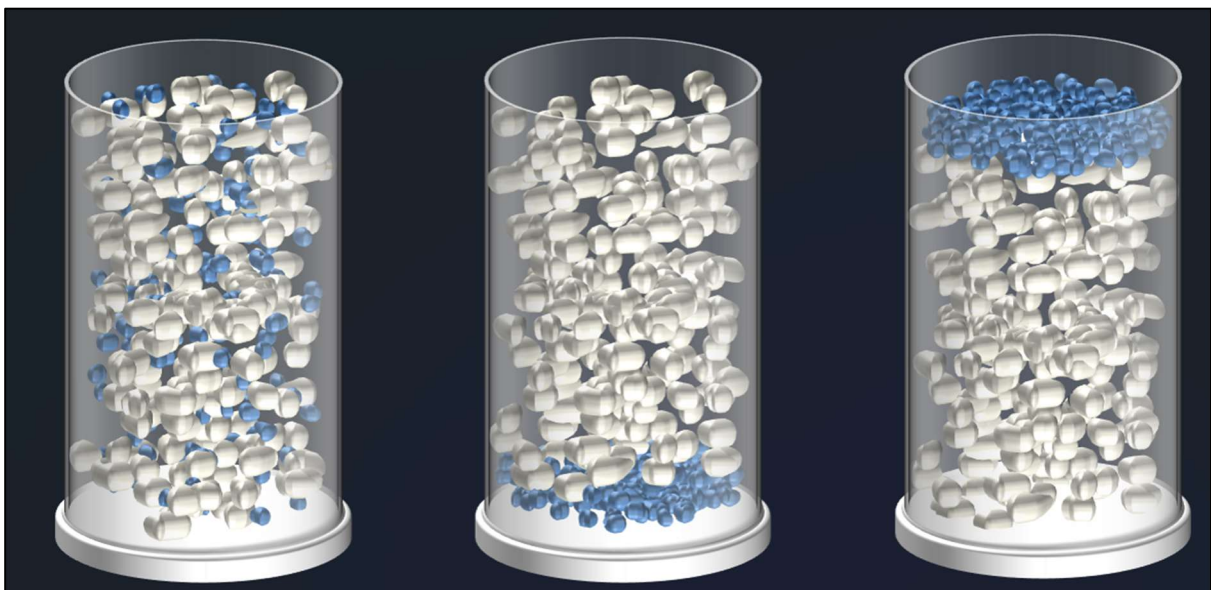


Figure 20 – Particle Segregation Schematic Courtesy of (Freeman, 2021)

Historically, WCL used plastic containers for sample collection, but high powder temperatures (200°C) often damaged these containers. Initial investigations led to replacing plastic with a steel jug, which better preserves the sample before transferring it to plastic containers for storage. However, this method introduces potential contamination as the powder is exposed to atmospheric conditions and WCL's surroundings. Once cooled, the sample is processed through a riffler, as shown in figure 21, several times to obtain a representative sample for analysis.



Figure 21- Riffler Used at WCL

The ASTM standard suggests alternatives to riffler use, such as rotary cone sample dividers or sampling probes, which offer more homogenous samples. However, rotary sampling is time-intensive, and WCL's current resources are insufficient for this method, making it impractical for operations to implement. Figure 22 provides an example of a rotary sampling setup.



Figure 22 - Spinning Riffler Example Courtesy of (Retsch, 2022)

Sampling probes, previously tested at WCL, faced durability issues due to material abrasion, which caused rapid damage to the probes. Given WCL's existing batch data on chemical composition and PSD, changing the sampling method for this study could introduce inconsistencies, potentially affecting the validity of results. Additionally, as shown in figure 23, powder can lodge in the sliding hatch of the probe, preventing proper closure and leading to contamination when handling multiple products.

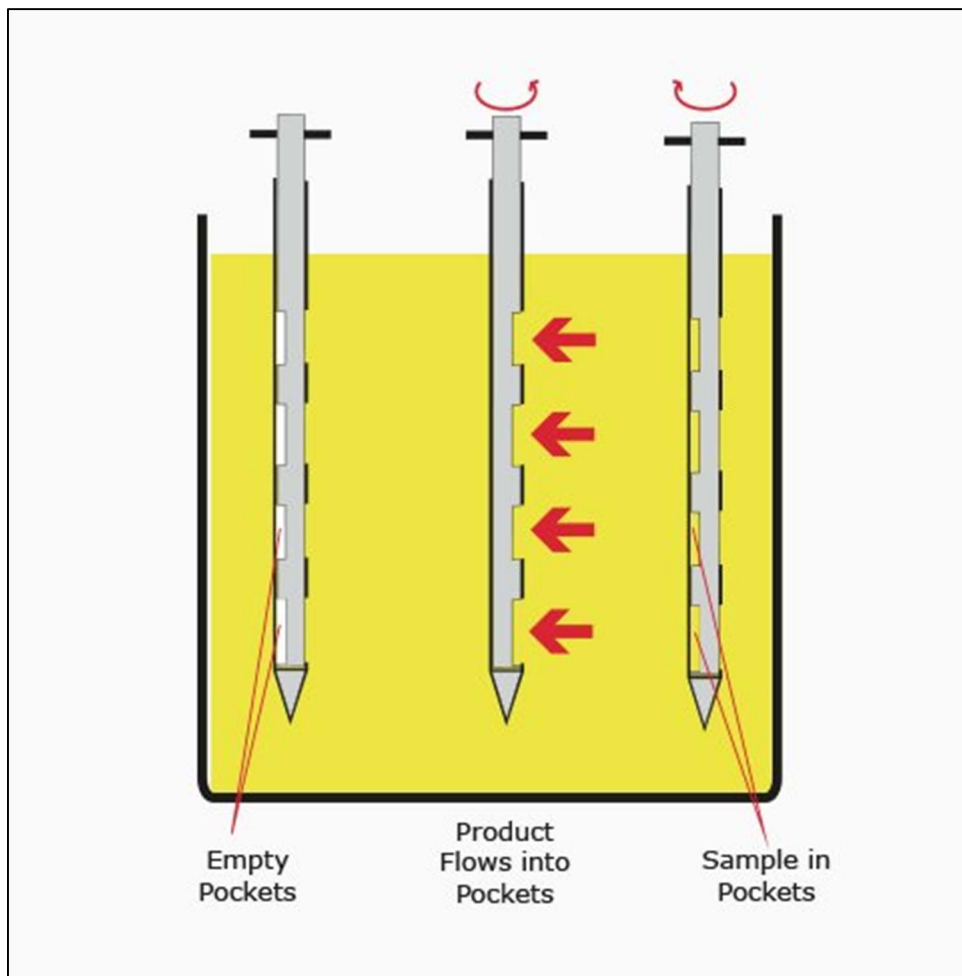


Figure 23 – Inline Sampling Probe (GMP, 2023)

2.9. Lean Techniques

The Define Measure Analyse Improve Control (DMAIC) methodology is a cornerstone of Lean and Six Sigma process improvement frameworks, providing a structured approach to identifying and resolving inefficiencies in industrial operations, as outlined in figure 24. Its application spans various sectors, including manufacturing, healthcare, and supply chain management, making it a versatile tool for systematic enhancement of processes.



Figure 24 – DMAIC Framework Courtesy of (Loebick, 2020)

The Define phase establishes the scope and objectives of a project, aligning stakeholder expectations and identifying critical processes requiring improvement. According to (George, 2005), the clarity achieved during this phase is instrumental in preventing scope creep and ensuring that subsequent phases remain focused. For screening technology, this phase involves characterising the performance bottlenecks, such as inefficiencies in handling fine-grade powders and the limitations of outdated equipment. Studies by (Antony, 2011) emphasise that a well-defined problem statement is pivotal for successful implementation of Lean projects, ensuring that organisational goals are met efficiently.

During the Measure phase, baseline data is collected to understand the current state of the process. This phase leverages statistical tools and metrics to quantify inefficiencies, such as throughput rates, yield, and right-first time (RFT) quality. (Harry & Schroeder, 2000) highlight that accurate data collection is the foundation for evidence based decision making. In the context of screening technologies, tools such as laser diffraction and Ro-Tap sieving are invaluable for evaluating particle size distribution and morphology. Furthermore, control charts and Pareto analyses are often employed to identify critical variables that influence process performance.

In the Analyse phase, the root causes of inefficiencies are identified using advanced analytical methods. Ishikawa diagrams, regression analyses, and hypothesis testing are commonly used to uncover correlations between process variables and outcomes (Pyzdek & Keller, 2014). For instance, studies by (Juran & Feo, 1999) demonstrate the utility of Design of Experiment (DOE) methodologies in isolating key factors that affect screening efficiency, such as feed rate, screen aperture size, and particle morphology. In screening processes, adhering to ASTM B214 standards ensures that analyses are both robust and compliant with industry norms.

The Improve phase involves implementing solutions derived from analytical insights. Lean principles advocate for iterative testing of changes, such as optimising screener parameters or incorporating new technologies like ultrasonic sieving enhancements. Studies by (Liker, 2004) highlight the importance of Kaizen, or continuous improvement, in achieving incremental gains. In the context of screening technologies, this phase might involve pilot testing optimised configurations or investing in hybrid solutions that combine vibratory screening with air classification for enhanced throughput and yield.

Finally, the Control phase ensures the sustainability of improvements through ongoing monitoring and refinement. This phase typically includes the establishment of Standard Operating Procedures (SOPs), control charts, and training programs to institutionalise best practices (Montgomery, 2013) emphasises that post-implementation audits and performance reviews are critical to preventing process regression. For screening technologies, performance monitoring systems can track key metrics such as yield and RFT rates, ensuring that the implemented solutions deliver consistent value over time.

The DMAIC methodology's structured approach aligns seamlessly with the objectives of screening technology optimisation. By defining the specific inefficiencies of current processes, measuring critical variables, and analysing root causes, organisations can implement targeted improvements while maintaining control over outcomes. Literature by (Bendell, 2006)

underscores that Lean initiatives leveraging DMAIC have demonstrated measurable benefits in reducing waste, improving efficiency, and enhancing product quality across various industrial applications.

In conclusion, the DMAIC framework provides a robust foundation for process improvement in screening technologies, offering a pathway to address both technical and operational challenges. Its emphasis on data-driven decision-making, iterative testing, and sustainable practices ensures that organisations can achieve strategic objectives while fostering a culture of continuous improvement.

2.10. Summary of Research

The production of nickel and cobalt-based alloys represents a complex and multifaceted industrial process, requiring precision and meticulous control across numerous interconnected stages. These alloys are critical for applications demanding exceptional material performance, including aerospace, additive manufacturing, and other high-technology sectors. This research explores the pivotal role of screening technologies in this production chain, elucidating its profound impact on process efficiency, product quality, and environmental sustainability. By critically evaluating these technologies, this study emphasises the dynamic interplay between operational innovations and ethical imperatives in advancing alloy manufacturing methodologies.

The production process begins with the precise formulation of raw material charges to achieve targeted chemical compositions. Following this, atomisation, a cornerstone process, rapidly cools molten metal to produce fine powder particles with tailored characteristics. These powders are subsequently dried to remove residual moisture, screened to ensure uniform particle size distribution (PSD), blended for compositional consistency, and packed under tightly controlled conditions to safeguard integrity and prevent contamination. Screening technologies, a key focus of this study, play a decisive role in achieving the desired PSD, which directly influences the alloy's mechanical properties, flowability, and uniformity. Effective PSD control is critical to ensuring compliance with the stringent standards demanded by high performance industrial applications.

This investigation evaluated three principal screening technologies being, vibratory screening, rotary screening, and air classification. Each was scrutinised for its capacity to optimise throughput, yield, and right-first time (RFT) performance, particularly when processing fine-grade powders below 20 microns. Vibratory screening, enhanced with ultrasonic technology, demonstrated exceptional precision and effective mesh deblinding capabilities, making it well-suited for ultra-fine powders prone to clogging and inefficiencies. However, limitations in scalability posed challenges for application in high volume industrial contexts. Rotary screening, by contrast, offered notable advantages in throughput and cost efficiency when handling coarser particles, yet its performance was hindered by mesh blinding and inefficiencies when processing ultra-fine powders. Air classification excelled in segregating particles based on aerodynamic properties, achieving narrow PSDs with high accuracy, but its efficacy declined significantly for ultra-fine particle sizes, limiting its broader applicability.

The study identified several key factors that critically influence screening efficiency. Particle morphology emerged as a central determinant, with irregularly shaped particles, such as elongated or agglomerated forms, significantly impairing separation performance. Spherical particles, by contrast, facilitated optimal screening outcomes. Feed rate optimisation was equally crucial, as excessively high feed rates compromised screen integrity and operational reliability, while low feed rates reduced productivity. Furthermore, adherence to ASTM standards for particle size analysis provided a robust and standardised framework for evaluating and comparing the performance of different screening technologies, ensuring consistency and reliability in the findings.

Ethical and environmental considerations surrounding nickel production constituted another significant dimension of this research. The environmental impact of nickel extraction, including deforestation, water pollution, biodiversity loss, and carbon emissions, is considerable. These challenges are further compounded by social issues, such as community displacement and labour exploitation, including instances of forced and child labour. Addressing these concerns requires a comprehensive and integrated approach, incorporating ecofriendly mining practices, adherence to stringent labour standards, and the adoption of responsible sourcing policies. Such measures not only mitigate the environmental footprint of production but also align with global sustainability objectives and ethical manufacturing imperatives.

The findings of this research suggest that hybrid approaches, combining vibratory screening with air classification, present a compelling solution for achieving enhanced efficiency, higher yield, and improved RFT performance. By leveraging the complementary strengths of these technologies, such hybrid systems overcome individual limitations, offering a balanced and adaptable framework for screening fine-grade powders. Moreover, the configurability of hybrid systems enables continuous improvement and scalability, aligning them with evolving production demands and long-term operational goals.

In conclusion, this study underscores the critical role of advanced screening technologies in the production of nickel and cobalt-based alloys. By addressing both technical and ethical challenges, the research offers a comprehensive framework for optimising screening processes and fostering sustainable and socially responsible manufacturing practices. These findings contribute to the development of more efficient production methodologies, supporting the industry's transition toward greener, more equitable, and technologically sophisticated solutions.

2.11. Hypothesis

Existing research typically focuses on single method screening technologies leaving a critical gap in understanding the potential advantages of combining screening methods. New technologies, such as advanced vibratory screening, claim to achieve high efficiency for fine particulates. There is limited evidence supporting these claims or its ability to handle even finer particle sizes effectively. This research addresses the gap by exploring the potential of hybrid screening approaches to optimise throughput, yield, and efficiency in metal powder screening. With the growing demand for fine powders in additive manufacturing and pharmaceutical applications, it is imperative for Wall Colmonoy to leverage innovative screening solutions to enhance product quality, reduce material losses, and remain competitive in the market by improving profitability.

3. Screener Selection Criteria

The selection of sieving equipment for the production of nickel and cobalt-based alloys demands rigorous evaluation of performance capabilities to align with stringent industrial standards. Central to this assessment is the equipment's ability to deliver precise particle size distribution (PSD) control, particularly for ultra-fine particles below 20 microns or other critical size thresholds. The equipment must ensure high throughput rates while achieving target separation cut points with minimal material loss, thereby enabling right-first time (RFT) quality and obviating the need for subsequent reprocessing.

Material compatibility forms a fundamental aspect of equipment selection. The sieving system must efficiently handle diverse particle morphologies, including elongated or agglomerated forms, without compromising operational efficacy. Furthermore, the system must accommodate high-density or reactive powders while maintaining contamination-free operations to preserve the integrity of the screened material. The equipment's ability to adapt to varying material characteristics is essential for ensuring consistency and reliability across production scales.

Scalability and throughput capacity are pivotal considerations, as the equipment must meet both current and future production demands. It should effectively manage feed rates up to 300kg/hr while demonstrating proven efficacy in both small-scale trials and large-scale industrial applications. This scalability guarantees that the equipment remains viable as production needs evolve, supporting both operational flexibility and capacity expansion.

The technological sophistication of the sieving equipment is a critical determinant of its suitability. Vibratory screening systems should incorporate ultrasonic enhancements to mitigate mesh clogging and enhance separation efficiency. Adjustable settings for frequency, amplitude, and lead angle are imperative for fine-tuning performance. Vibratory screening systems must prioritise designs that reduce mesh blinding and facilitate straightforward maintenance, while variable speed controls enable dynamic throughput adjustments. For air classification systems, the integration of computational fluid dynamics (CFD) for precise airflow modulation and high-speed rotors for achieving narrow PSDs represents an advanced and effective solution.

Operational efficiency and maintainability are essential for sustained performance. The equipment must be designed for ease of cleaning and maintenance, with simplified screen replacement mechanisms that minimise downtime and mitigate contamination risks. Durability is non-negotiable as the equipment should utilise high-quality mesh and robust structural

components to ensure longevity and resist degradation under prolonged use. Additionally, advanced dust control features are imperative for maintaining a safe and environmentally compliant workspace.

Environmental sustainability and ethical compliance must underpin the selection process. The equipment should align with eco conscious operational goals, including minimising energy consumption and waste generation. Manufacturers must adhere to ethical labour practices and responsible sourcing protocols, ensuring the equipment contributes to broader sustainability initiatives. The integration of environmentally responsible manufacturing practices reinforces the ethical integrity of the production process.

Cost considerations should balance initial capital expenditure (CapEx) with long-term operational expenditure (OpEx). The total cost of ownership must be evaluated in the context of expected efficiency gains, product yield improvements, and reduced maintenance or energy expenses. The financial outlay should reflect the equipment's ability to deliver sustained economic and operational benefits over its lifecycle.

Adaptability to hybrid configurations is another key factor in equipment selection. The capability to integrate with complementary systems, such as combining vibratory screening with air classification, enhances overall operational flexibility and performance. Such adaptability ensures that the equipment remains aligned with emerging technological advancements and evolving production requirements.

Finally, compliance with established industrial and quality standards is imperative. Adherence to protocols such as ASTM E11 ensures consistent performance and reliability. Preference should be given to equipment with a demonstrated history of success in similar applications or systems validated through independent testing and rigorous trials.

By adhering to these comprehensive criteria, manufacturers can ensure that the selected sieving equipment meets the highest operational, environmental, and economic standards. This methodical approach facilitates superior screening outcomes, enhances production efficiency, and supports sustainable and ethically responsible manufacturing practices in alloy production.

4. Trial Plan

The primary goal of this initial trial was to compare three screening methods in the form of vibratory screening, rotary screening, and air classification, in order to identify the most efficient method in terms of quality, yield, Right First Time (RFT) improvements, and throughput. Once the most efficient screener is determined, a follow-up trial will focus on optimising the most efficient screener, to further improve performance. Both vibratory and rotary screeners will be conducted using a 450kg batch of material with identical particle size distribution (PSD), a feed rate of 150 kg/h, and a 60-micron screen.

4.1. Material Preparation

Before starting the trials, the 450 kg batch of material was homogenised to ensure uniformity in PSD across all the experiments. A twin-cone blender was used to achieve thorough mixing, which helped maintain consistency when the batch was divided for the screening processes, as shown in figure 25. The blending process takes approximately 30 minutes, with intermittent checks to ensure uniform mixing throughout the material. After blending, samples will be taken from various points in the batch to confirm consistency by performing sieve analysis, as outlined in the literature review. This step ensures that all screening methods are tested under identical conditions, eliminating any variations in feed material.



Figure 25 - Blender used at Wall Colmonoy

4.2. Trial 1 – Direct Comparison of Screeners

As described in the literature review, the vibratory screener separates particles through vibratory motion, while the rotary screener operates with rotating movements to achieve particle separation. The air classifier uses airflow and centrifugal forces to divide particles based on size. The first set of trials are set up to see what differences are observed, opposed to the theory which are throughput, yield, and quality.

Three variables will be measured as a result of these trials, throughput will be measured as the time taken to screen the entire batch, while yield will be determined by the amount of product that meets the specification compared to the input material, as seen in equation 1.

$$Yield (\%) = \left(\frac{\text{Product Fraction}}{\text{Input Material}} \right) \times 100$$

Equation 1 - Yield Equation

Quality will be assessed by performing sieve analysis to evaluate the precision of particle separation. Utilising laboratory equipment at Wall Colmonoy such as scanning electron microscopy analysis, and Malvern Morphologi M4 will allow particles to be analysed to determine how spherical the particles are. RFT, which measures whether the screened product meets the required specifications in the first pass, will also be recorded. The goal is to understand how each screening method performs in terms of throughput efficiency, the precision of separation, and the yield of the final product. Based on the atomised distribution, the maximum yield that could be achieved is 53%, which has been calculated by summing the percentage of particles that are between the product bands shown in the table below.

Particle Range	%Min	%Max	Max Achievable	Rotary	Vibrating	Air Classification
>75	0.0%	0.0%	12.45%	0.0%	0.0%	0.0%
75-63	0.0%	0.2%	5.48%	0.1%	0.0%	0.0%
63-53	0.0%	10.0%	6.45%	3.3%	0.0%	0.0%
53-45	15.0%	35.0%	7.18%	25.8%	10.0%	0.0%
45-38	17.6%	75.0%	7.78%	26.9%	40.0%	0.0%
38-20	15.0%	40.0%	31.24%	33.4%	45.0%	75.0%
<20	0.1%	0.4%	29.42%	0.5%	5.0%	25.0%

Table 1 - Comparison of Screening Technology

The results shown in table 1 compare a screening comparison between rotary, vibratory, and air classification. To measure the number of particles in each particle range, 100 grams of powder is put through the sampler and the results are summed between the product bands to give an overall percentage. For the comparison between rotary and vibratory screening, the

same batch of powder was used, the throughput was set to 150kg/hr on each screener by utilising the loss in weight feeder, as shown in figure 26, along with the same screen size being used. It is clear to see from the results that the rotary screener nearly achieved a right first-time pass, and only missed out on the bottom band by 0.1%. Whereas the vibratory screener was out of specification in several areas, which would require rescreening to meet the specification. The material was blended and passed through the air classifier, which has a cut point of 20 μ m, therefore only measures plus or minus the value. The air classifier cut 25% - 20 μ m which is around 85% of the available PSD.



Figure 26 - Pinch Valve LIW Feeder at WCL

5. Virto – Vibratory Screener

Vibratory screening has two methods for screening. The conventional way has the motor on the centre line, and the newer method Virto offer have motors on the side of the unit. This method has claimed to have over 99% screening efficiency. In this section an investigation takes place to prove this claim as this would have exponential improvements to the business. Figure 27 shows the Virto at WCL ready for trials.

In this trial, there are several variables being measured. One of which is the screen clear time which is analysing how long after the material has been fed onto the screen, does it take to clear into the retrospective fractions. This will be done by looking through an inspection hatch and using a stop watch. If the material does not seem to be moving, then this will be removed from the screen and weighed. To control the feedrate, the loss in weight feeder will be used. When analysing the efficiency of the unit, the product outlet will be weighed using a weighing scale and compared to the input material to give an overall yield percentage. To determine how much product was not screened efficiently and was in the $<20\mu\text{m}$ section, laser diffraction will be used to determine the amount.



Figure 27 - Set up of Trial using Virto Screener At WCL

The Virto ScreenX is an advanced multi-frequency screener designed to separate powders with varying particle size distributions (PSDs) efficiently. This screener employs two motors and an internal beater to apply 400-500 Gs of force on the mesh, facilitating particle separation. It operates at adjustable frequencies, between 42 and 52 Hz, causing the powder to rotate in a clockwise direction around the sieve, enhancing separation. Where, any particles below the mesh aperture will go through the mesh, and any particles bigger than the mesh aperture will feed out of the outlet as shown in figure 28. This section describes the equipment setup, procedures, and results from two trials that assess the efficiency of the ScreenX under different conditions.

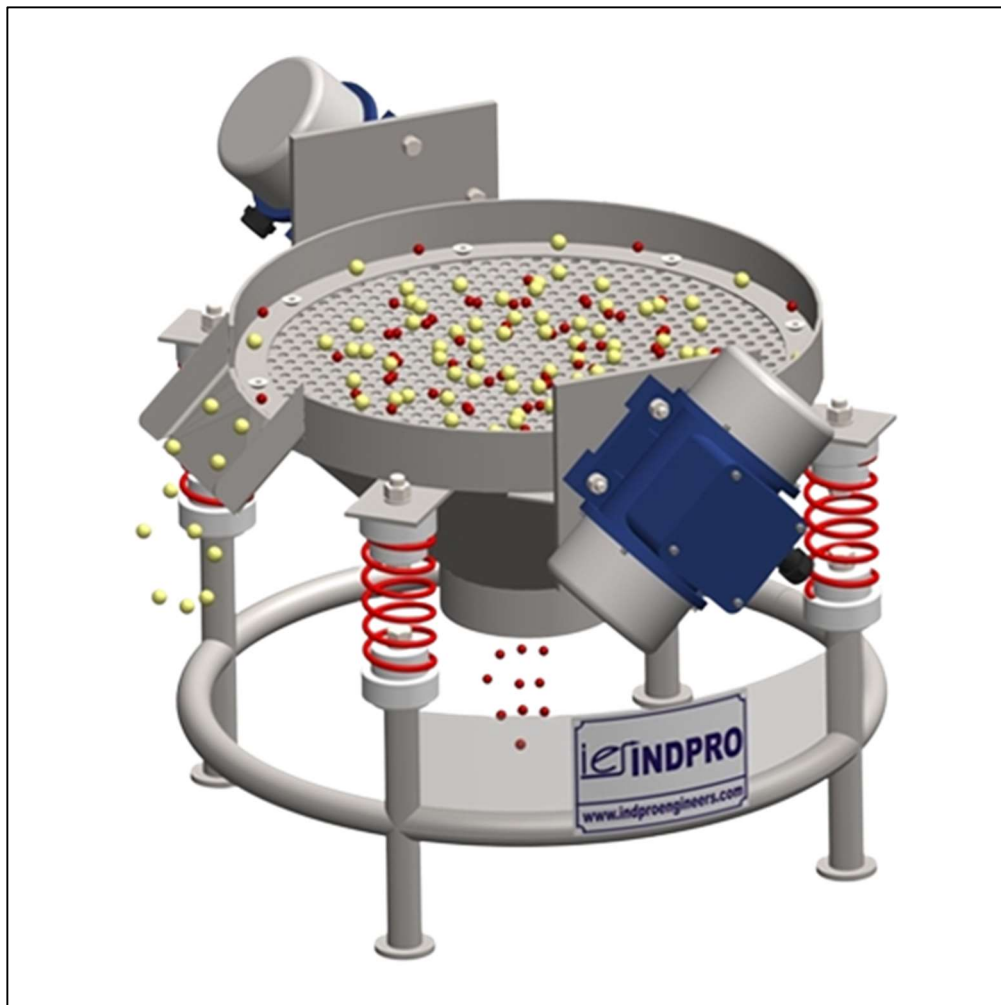


Figure 28 – Example of Virto Screening Technique (Indpro, 2024)

5.1.1. Initial Trial Set Up

For the trials, the Virto ScreenX was configured using practical and cost-effective collection methods, as this was a small scale trial, insignificant weight would cause injury. Bags were taped to the outlets for powder collection, with kegs used to support the weight of the bags shown in figure 29.



Figure 29 – Equipment Set Up

The equipment setup involved removing the top section to expose the internal beater, which plays a vital role in the screening process. The screen is positioned above the beater and clamped down by the top section. The screen assembly consists of several layers. The main metal ring provides structural support, as shown in figure 30.



Figure 30 - Beater Ring of the Virto Screener

On this, a 3mm stainless steel (S/S) support screen is welded, followed by a 200-micron screen that is tensioned and glued onto the S/S screen, as shown in figure 31. A working screen is placed flat on top and secured by taping the edges. The entire screen setup is sealed using a rubber ring, which holds the screens in place and prevents leakage during operation. Minimal tension is applied to the working screen to prevent sagging or damage, ensuring that particle size separation remains accurate.



Figure 31 - Powder Scraper on the Virto Screener

The top plate of the screener contains a metal bracket that houses two small rubber pieces. These rubber pieces serve to redirect the powder, ensuring that only the product exits through the product outlet. They are both removable and adjustable, allowing fine control over the amount of powder cleared from the screen, as shown in figure 32.

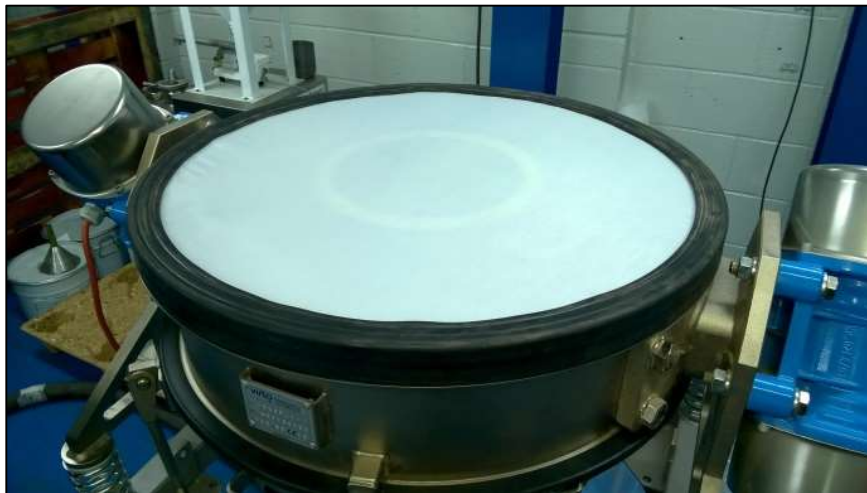


Figure 32 - Screen Set up for the Virto

5.1.2. Cleaning Procedure

After each screening operation, the Virto ScreenX must be cleaned to remove excess powder. The cleaning process begins with vacuuming the screener once the top section has been removed. Given the potential for static shocks, care must be taken when vacuuming the powder. After vacuuming, the bottom section is removed to prevent the swing bolts from vibrating loose, and the machine is briefly run to ensure it is completely clean. Once clean, the machine is reassembled, and the screen may be replaced if necessary.

5.1.3. Results of Trials

The objective of the trials was to assess the separation efficiency of the Virto ScreenX at various feed rates and for different PSD requirements. The trials focused on determining how well the screener separated particles below specific size thresholds for two different powders.

In the first trial, the screener was tested using a 60-micron screen on a batch size of 5 kg with a feed rate ranging from 15 to 120 kg/h. The main objectives of this trial were to assess screen efficiency, feed rates, particle size distribution (PSD), and powder loss. As shown in table 2 the screening efficiency was excellent and efficient, there was a tight range (87%-91%) and feed rate did not have an impact.

Feed Material (Kg)	Feed Rate (Kg/h)	Screen Clear Time	Reclaimed product Weight (kg)	Product in the -20µm	Screening Efficiency
5	15	2m 30s	2.4	8%	91%
5	22	2m 54s	2.3	12%	87%
5	30	1m 48s	2.3	12%	87%
5	60	2m 23s	2.3	12%	87%
5	90	1m 46s	2.4	10%	91%
5	120	2m 24s	2.4	10%	91%

Table 2 – Initial Results from Virto Trials

During the test at 120 kg/h feed rate, approximately 600 grams of powder remained on the screen after a 2-minute 44-second clear time. This retention suggests that material continued to adhere to the screen, despite no visible powder discharging after the clearing process had concluded. This raises the concern, if on a larger throughput campaign, the screen pegging would increase and affect screening efficiency. Based on the data seen in table 2, there was a carryover of up to 12% in the +20µm, making this type of technology more efficient compared to previous technology used.

The particle size distribution (PSD) data for Trial 1 showed consistency across different feed rates, with only minor variations attributed to natural product variation rather than process issues, as shown in figure 33. The standard deviation demonstrates between these bands was less than 1% which shows the machine is highly efficient. This consistency suggests that the screener maintained effective performance, even at higher feed rates. Additional trials with feed rates above 120 kg/h would have been beneficial to further assess the machine's capacity.

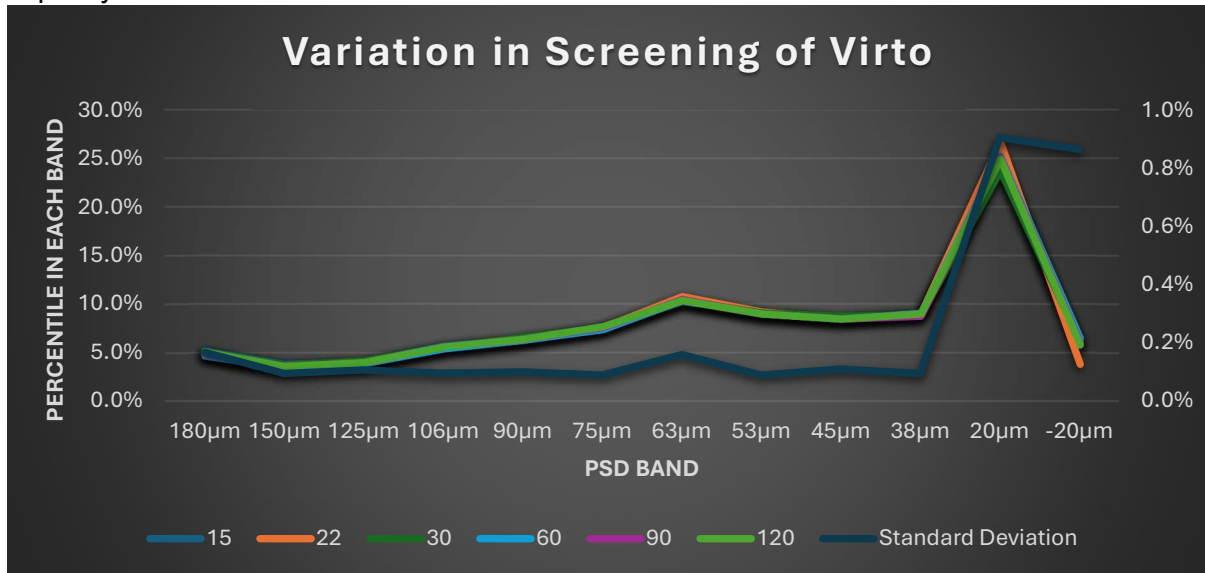


Figure 33 - Screening Variation of the Virto

From chemical composition analysis contamination was a concern during Trial 1, as 1.5% of the powder screened contained copper-bronze powder. This contamination was likely caused by the design of the screener, making thorough cleaning challenging. In larger scale manufacturing, labour cost would increase for non-value-added activities and risk writing off all profits which would have a detrimental impact on the business.

Theoretical yield was calculated using the PSD results, particularly focusing on the +90µm cutoff and -20µm as per the specification. The highest feed rate of 120 kg/h yielded a practical yield of 48% vs a theoretical yield of 53%. This is a 54% improvement on the current yield of 22% and would result in significant improvement to the business, such as increasing annual revenue if the product met the specification on a right first time basis. Thus, the initial trials give an overall efficiency of 91% as shown from equation 2, based on the ratio of theoretical product reclaimable to actual product reclaimed.

$$\text{Relative Efficiency} = \frac{48\%}{53\%} \times 100 = 91\%$$

Equation 2 - Relative Efficiency

5.2. Increased Production Trial

The main objective of this trial was to assess the potential improvements in the efficiency and reliability of product screening on a bigger scale. Various powders were used during the trials, and different screen sizes were applied to determine the precision of cuts made by each mesh. Additionally, efforts were made to maximise feed rates to identify the optimal conditions for achieving right-first time (RFT) production.

This secondary trial will follow similar patterns from the initial trial when it comes to obtaining and analysing the data. The loss in weight feeder, along with weighing scales, will be used to measure the outputs from the screener and to calculate yield. Sieve analysis will be conducted to further investigate the efficiency of the screener. This will be conducted using rotap testing for +20 μ m particles and laser diffraction for the finer grade particles. This will then be compared to the specification sheet, like shown in figure 34, which will determine whether the powder has met the specification on a right first time basis.



 WALLCOLMONOY

Wall Colmonoy - Powder Production Specification

Wallex 6-P2 Powder
PWX6-P2

Lot #

QTY (KG)

Lab Testing & Material Specifications

Element Name	Min	Max	Aim	ICP Result
Boron (B)	0.000	0.050	0.000	
Carbon (C)	0.900	1.400	1.200	
Chromium (Cr)	27.000	31.000	29.000	
Cobalt (Co)	51.990	68.600	60.100	
Combined Others (Ot)	0.000	0.500	0.000	
Iron (Fe)	0.000	3.000	1.500	
Manganese (Mn)	0.000	1.000	0.500	
Molybdenum (Mo)	0.000	1.000	0.500	
Nickel (Ni)	0.000	3.000	1.500	
Nitrogen (DNQ) (N)	0.000	0.200	0.000	
Oxygen (O)	0.000	0.100	0.000	
Phosphorous (P)	0.000	0.030	0.000	
Silicon (Si)	0.000	1.500	1.200	
Sulphur (S)	0.000	0.030	0.000	
Tungsten (W)	3.500	5.500	4.500	

ICP Test
Sign

Particle Range	% Min	% Max	Result
>180	0	0	
180 - 150	0	5	
150 - 125	7	20	
125 - 63	Bal	Bal	
63 - 53	6	18	
53 - 45	0	7.5	
45 - 38	0	2	
<38	0	0.5	

Particle Test
Sign

Code	Test Description	Test Details	Result
Half Flow	ASTM B-213	Data Capture Only	
Apparent Density (Spray + PTA Grades)	ASTM B-212	Spec = 4.0-5.0g/cm ³ , Internal Specification.	

Method Name	Description	UOM	Min	Max	Result	Avg.	Comments
Atomising Melt Coupon	Ceramic Coupon	Rockwell C	38	46			
PTA Weld Test	2 Layered Deposit - Mild Steel Block	Rockwell C	38	46			

Figure 34 - Example Specification

As the initial trials were deemed a success, Virto allowed a unit to be kept on site in order to conduct further testing. The second trial was conducted under more controlled conditions with improved weighing accuracy. However, several issues with the setup and screen size negatively impacted the trial results.

5.2.1. Installation Constraints

To allow the trials to occur, the first task involved designing the installation of the screening equipment using computer aided design software, providing a preview of how the machine would be set up. A challenge encountered during this design phase was managing the powder flow from the machine, which had two large outlets to the hopper with smaller inlets. Without proper management, this could have created a slip hazard due to spillage. To address this issue, reducers were fabricated to suit the process needs. Another constraint was the limited space behind the machine due to a redundant ledge from a previous process that had not been removed. This raised concerns about potential trapping hazards, which were noted in the risk assessment. A drawing illustrating this layout was included, as shown in figure 35. Once the design was finalised and agreed with the stakeholders, the installation proceeded with the maintenance team.

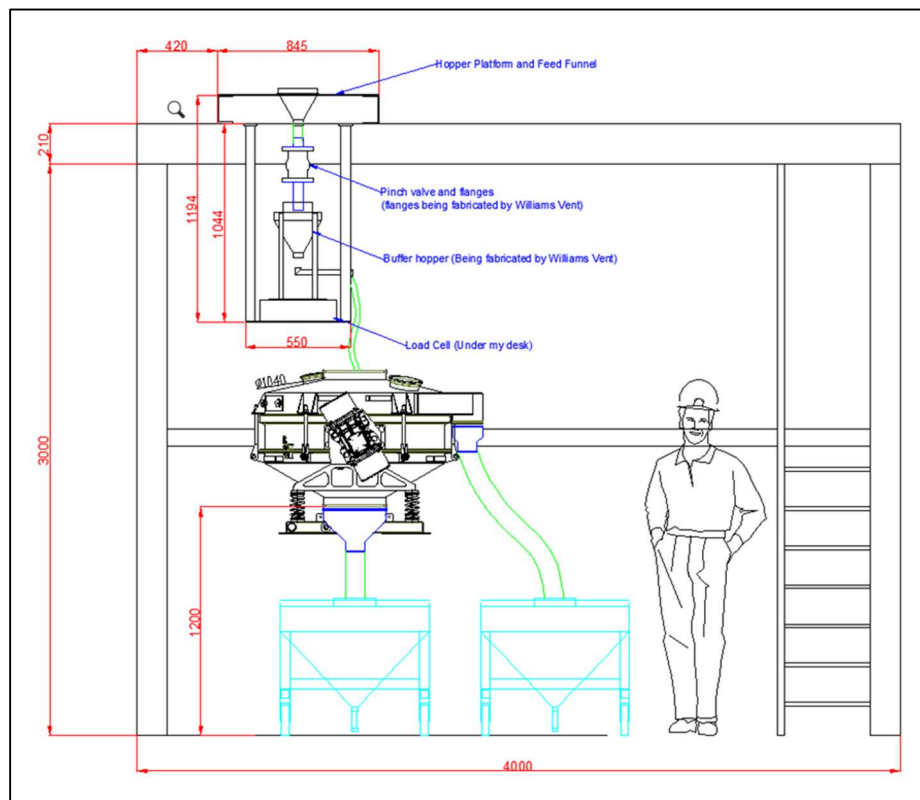


Figure 35 - Virtu Installation Drawing

5.2.2. Health and Safety

The choice of screen size and feed rate for the trials was made in consultation with the stakeholder. The setup process required assistance due to the size and weight of the screens, ensuring adherence to the company's lifting guidelines. As the machine was located in a powder room, appropriate personal protective equipment (PPE) was worn to comply with company policy and ensure safety in the dusty environment, which needed to follow the checklist in figure 36. A torque wrench was used to tighten the screen bolts to the specified torque, ensuring the machine could operate safely without putting operators at risk.



Figure 36 - PPE Requirement For Screening Powder

Although only one person was directly involved in running the trials, a risk assessment and standard work instructions were developed. These documents were placed near the machine to ensure operator safety during the trials. Maintaining a tidy workplace was critical to minimise health and safety risks and prevent cross-contamination.

In the event of an accident, the company had trained first-aid responders, and first-aid boxes were strategically placed around the factory. If the fire alarms were triggered, the protocol was to evacuate the building safely and proceed to designated fire assembly points. Figure 37 shows the location of trials and evacuation routes. Regular fire alarm tests were conducted on Fridays at 11 a.m. without requiring evacuation.

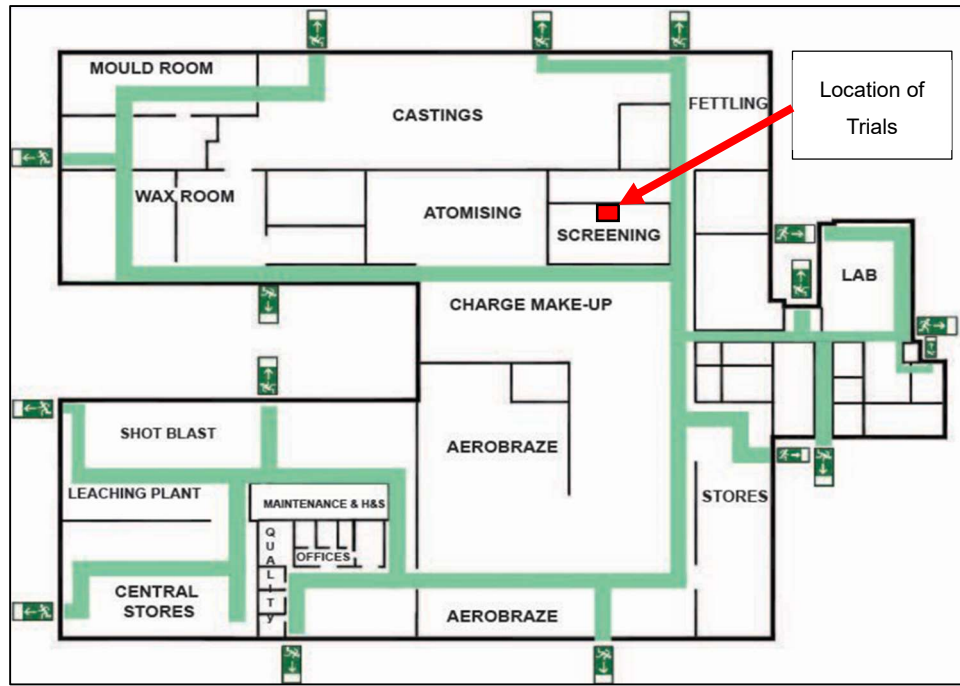


Figure 37 - Evacuation Route During Trials

5.2.3. Problems Encountered

During the trials, a screen malfunction halted progress, as shown in figure 38. The trials were suspended as no spare screens were available on-site. Regular communication with the manufacturers were maintained to resolve the issue. Several temporary solutions, such as applying tape on mesh patches, were considered but ultimately deemed insufficient due to the risk of inaccurate results. After discussions with stakeholders, the chosen solution involved either receiving a new backing mesh or adjusting the beater ring. The latter was successfully implemented in collaboration with the maintenance team, and no further issues occurred.

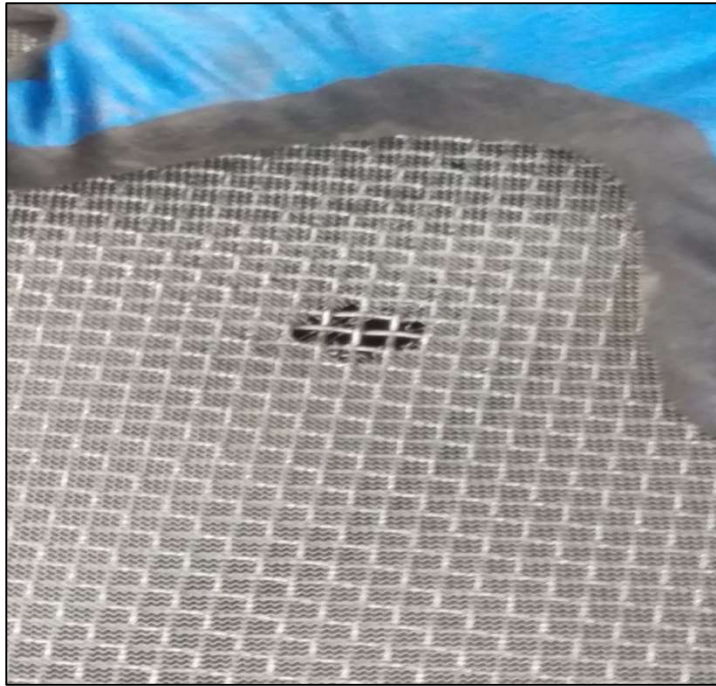


Figure 38 – Screen Damage

Instructions for adjusting the beater ring were followed meticulously, including disassembling, modifying the spacer, and reassembling the machine with the correct torque settings as outlined in figure 39. This maintenance task was prioritised according to the company's scheduling system, with detailed documentation submitted to both the maintenance team and the health and safety manager.

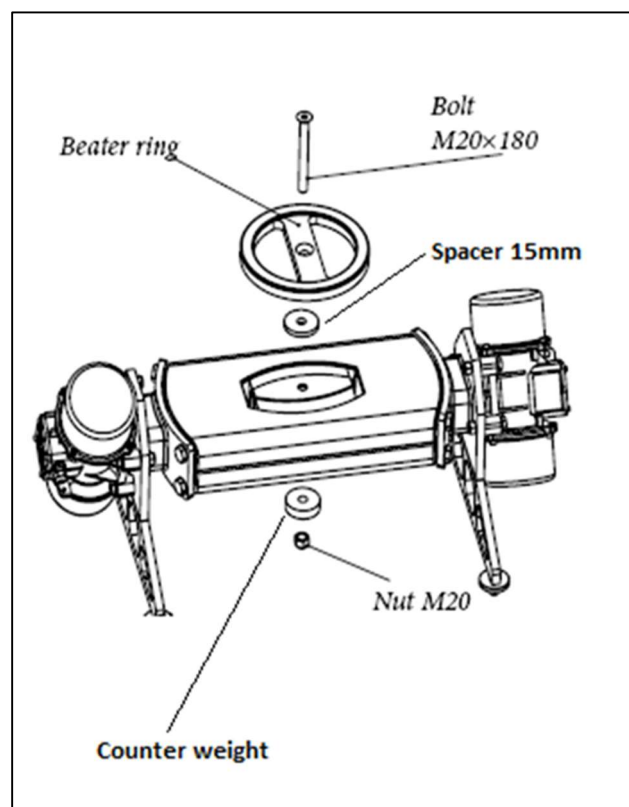


Figure 39 - Maintenance Guidance for the Virto

5.2.4. Results

The next set of trials performed on the Virto varied in batch size between 314kg to 678kg. This variance was due to the batch size from the atomising process which included losses in this manufacturing route. Nine trials in total were conducted where the feed rate varied from 150kg/hr to 300kg/hr. As shown in table 3, only one trial achieved a right first time pass and achieved a yield of 23% when run at 150kg/hr. In this trial set there were no consistent batches like the small scale trials, where yields were between 15% to 80%. However, as the majority of these results did not achieve a first time pass, the product would need to be rescreened which would reduce the final yield. When rescreening is needed, it not only reduces the final yield, but impacts operational costs as more energy is required to run the screener along with all the man hours with the additional screening operation. The need for rescreening creates a bottle neck in the process which can have an impact on the OTIF (on time in full) percentage, with missed deadlines which can negatively impact the organisation customer expectation and affect company brand.

Trial	A/A Weight (kg)	Feedrate (kg/hr)	Product (kg)	Yield	RFT?
1	639	150	241	38%	No
2	633	150	143	23%	Yes
3	596	150	183	31%	No
4	319	150	155	49%	No
5	322	150	105	33%	No
6	678	300	105	15%	No
7	320	300	255	80%	No
8	314	300	111	35%	No
9	588	300	98	17%	No

Table 3 – Results from the Second Trial on the Virto

The data from table 4 displays the sieving analysis performed on the 'product' section. The failed bands, highlighted in red, follow a common pattern where the samples were outside specification on all PSD bands bar 180, 150 and 90µm. This raised concerns over the validity of the screener and further trials aborted and the equipment sent back to Virto.

Trial	180	150	125	90	63	45	-38	Total
1	0.0%	0.5%	14.5%	32.8%	34.9%	16.0%	1.6%	100.3%
2	0.3%	0.4%	29.2%	50.3%	19.3%	0.5%	0.0%	100.0%
3	0.0%	5.5%	24.0%	43.6%	19.4%	3.3%	4.2%	100.0%
4	0.0%	3.1%	27.2%	46.4%	20.7%	0.7%	1.9%	100.0%
5	0.0%	2.4%	15.7%	40.2%	36.7%	4.4%	0.2%	99.6%
6	0.0%	3.0%	14.8%	37.0%	39.8%	3.7%	1.3%	99.6%
7	0.0%	3.2%	11.1%	37.0%	35.4%	7.6%	8.0%	102.3%
8	0.0%	4.7%	10.6%	42.9%	32.0%	2.4%	7.6%	100.2%
9	0.0%	2.9%	9.0%	44.1%	35.4%	2.4%	6.1%	99.9%

Table 4 – PSD Analysis from Trial B

Due to the ongoing problems with achieving the desired PSD at WCL, a batch of powder was sent to Virto for comparison trials at Virto's expense to try resolve the poor results. Sampling and analysis were conducted at Virto and WCL. There were discrepancies between the two sets of data and as a precaution, a reference sample was analysed on the sieve set at WCL and all was in calibration. It was later found Virto were not using sieves approved or calibrated to ASTM E11 which concluded this screening analysis.

5.2.5. Outcome

Based on the findings from the WCL trials, the Virto screener will not be considered for further progression due to the inefficiencies and challenges observed on-site. While the Virto screener showed some promising results at Virto HQ, these outcomes were not replicated during the trials at WCL. Although vibratory screening is beginning to transform the powder manufacturing industry, the technology is not yet advanced enough to replace established and proven methods.

Trial 2 encountered significant setup challenges due to the delivery of an incorrect screen size from Virto. Instead of the specified 60 µm screen, a 53 µm screen was provided. This screen was also improperly fitted to the chassis, likely leading to inadequate screen tension and potentially allowing undersized powder to pass through. Consequently, the data from Trial 2 was deemed unreliable for evaluating the screener's performance.

6. Ultrasonic Vibratory Screening

The second vibratory screener being trialled is in the form of the Russell Finex screener. As discussed in the literature review, this method of screening utilises a motor on the centreline of the unit which oscillates the screener to create the vibratory motion. From the research, it was discovered that in conjunction with feed rate, the use of ultrasonic sieves, controlling the lead angle and amplitude are pivotal factors in achieving the most optimisation from the screener.

There will be two main trials conducted. The aims of the first trials are to adjust these parameters to fully optimise the screener for the intended product. Then based on this setup data, large scale trials will determine how the screeners efficiency is held on long campaigns. To measure these aims, data will be gathered throughout each trial. To control the feedrate of material onto the screen, the loss in weight feeder will be utilised. For use of ultrasonic screens, these are a sperate design to normal which allows for ultrasonic vibration to be used. As these are clearly different, this will control which is an ultrasonic screen and which is not. When changing the lead angle and amplitude, there are clear markings within the base of the screener which will be logged on the trial sheet. Each output from the screener will be weighed using scales and each compared to the input material to give a percentage. Yield will follow the same calculation in each screener trail when the product hopper is compared to the input material to give the percentage. To determine if the product meets the specification, the product hopper is sampled and using laser diffraction and sieve analysis, the data will be analysed and compared to the specification to determine the pass succession.

6.1. Optimisation of Screening

A Design of Experiment (DOE) was conducted in conjunction with a Kaizen activity aimed at optimising the vibratory screener's parameters, to maximise yield and improve right-first time (RFT) percentages. This phase of the study allowed for more parameters to be controlled, such as feed rate, amplitude, lead angle, and the inclusion of ultrasonic screens to enhance deblending and extend screen life, as outlined in figure 40.

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 40 – Trial Parameters

6.2. Lead Angle

The lead angle, also known as the angle of inclination or attack, is the angle between the horizontal plane and the line of force generated by the vibratory motor. Adjusting this angle alters the material flow across the screen. A larger lead angle creates a more aggressive screening action, while a smaller angle results in a gentler screening process. At a 0° lead angle, material tends to move to the periphery of the screen without fully discharging, which is suboptimal for most applications, as illustrated in figure 41.

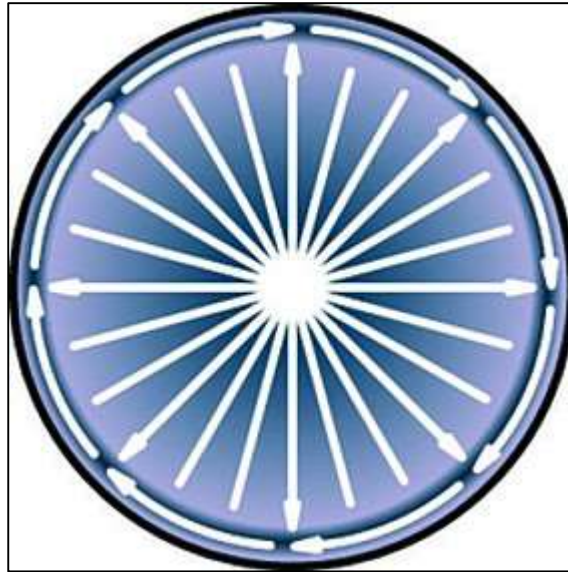


Figure 41 - Lead Angle at 0°

Lower lead angles result in radial material flow from the centre to the edges of the screen, whereas mid-level angles produce a spiral pattern, which maximises the material's dwell time on the screen surface. A lead angle of 30° - 35° (shown in figure 42) yielded the most efficient screening pattern as discussed by (Brock, 2011). However, higher lead angles may be required in applications such as scalping, where material must be retained on the screen for longer periods to ensure proper separation.

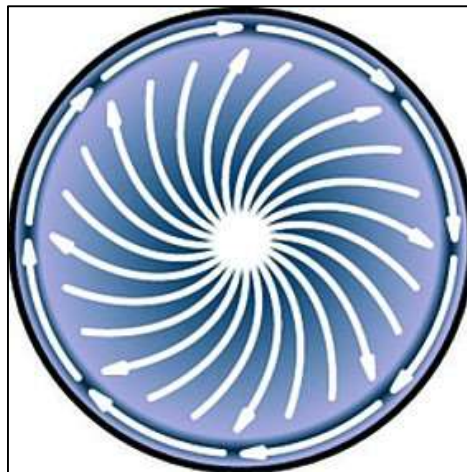


Figure 42 - Lead Angle between 30° & 35°

6.3. Amplitude

In vibratory screening, amplitude refers to the magnitude of the oscillatory motion imparted to the screen mesh, as outlined in figure 43, which are denoted as the 'heavy hammers'. It plays a critical role in determining the efficiency and effectiveness of the screening process for metal powders. Amplitude impacts the energy transferred to the particles, influencing movement across the screen and the likelihood of passing through the apertures. Higher amplitude generates more vigorous vibrations, which are particularly effective for breaking up agglomerates in cohesive metal powders and preventing screen blinding. This ensures that finer particles can pass through the mesh while coarser particles are efficiently separated.

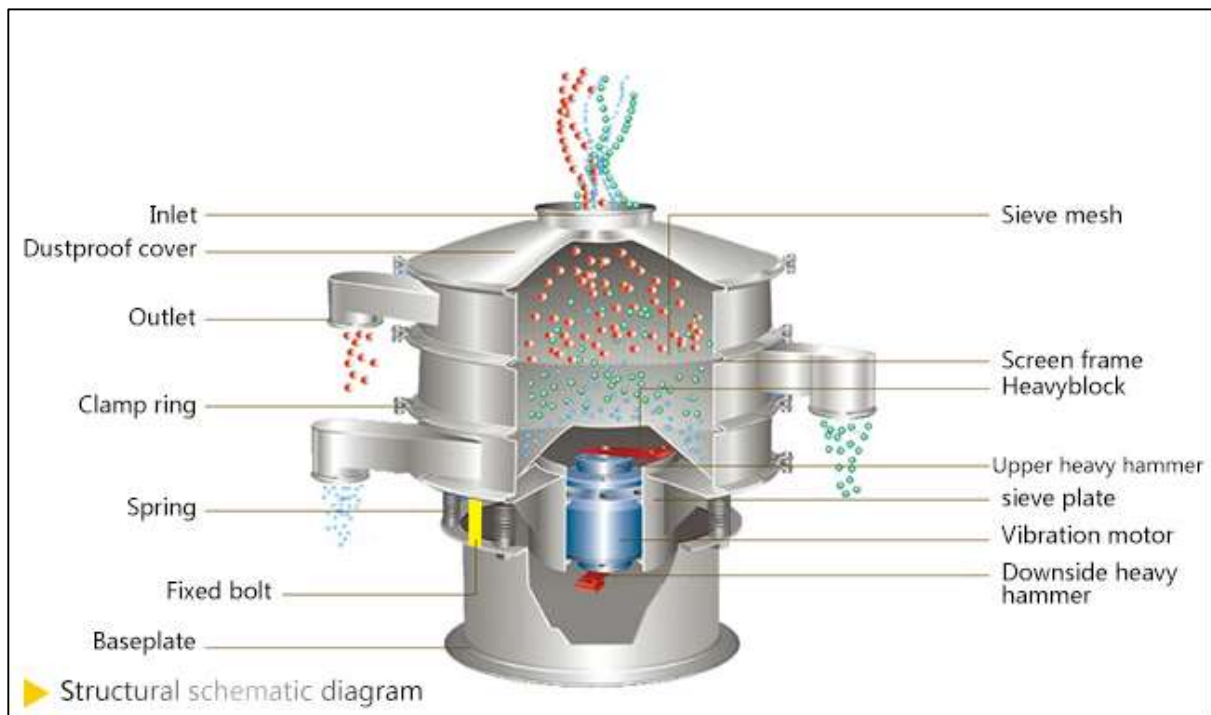


Figure 43 – Operational Schematic of Russel Finex Screener (Dahan, 2024)

For metal powder screening, amplitude must be carefully adjusted based on the characteristics of the material being processed. A low amplitude is better suited for delicate powders or when a precise particle size distribution (PSD) is required, as it minimises over-vibration that could cause particle degradation. Conversely, a higher amplitude is useful for heavier or stickier metal powders, as it provides the energy needed to keep material flowing evenly across the screen. Optimising amplitude is essential for achieving high-quality screening results, as it directly affects throughput, screening efficiency, and the consistency of the final product.

6.4. Results

Eight runs were conducted during the trials to determine the optimal settings, considering feed rates of 150 kg per hour and 300 kg per hour, with and without ultrasonic sieves, varying lead angles, and amplitude setpoints. On each trial, only one parameter was adjusted, and results recorded before adjusting the parameters and doing another trial. The key changes were standard feed rate which was set to 150kg/hr where the non-standard feed rate was 300kg/hr. Next was controlling whether the ultrasonic screen was used or not. The lead angle was set at either 60° or 90° based on the research shown, as well as the amplitude set between G:G or F:F.

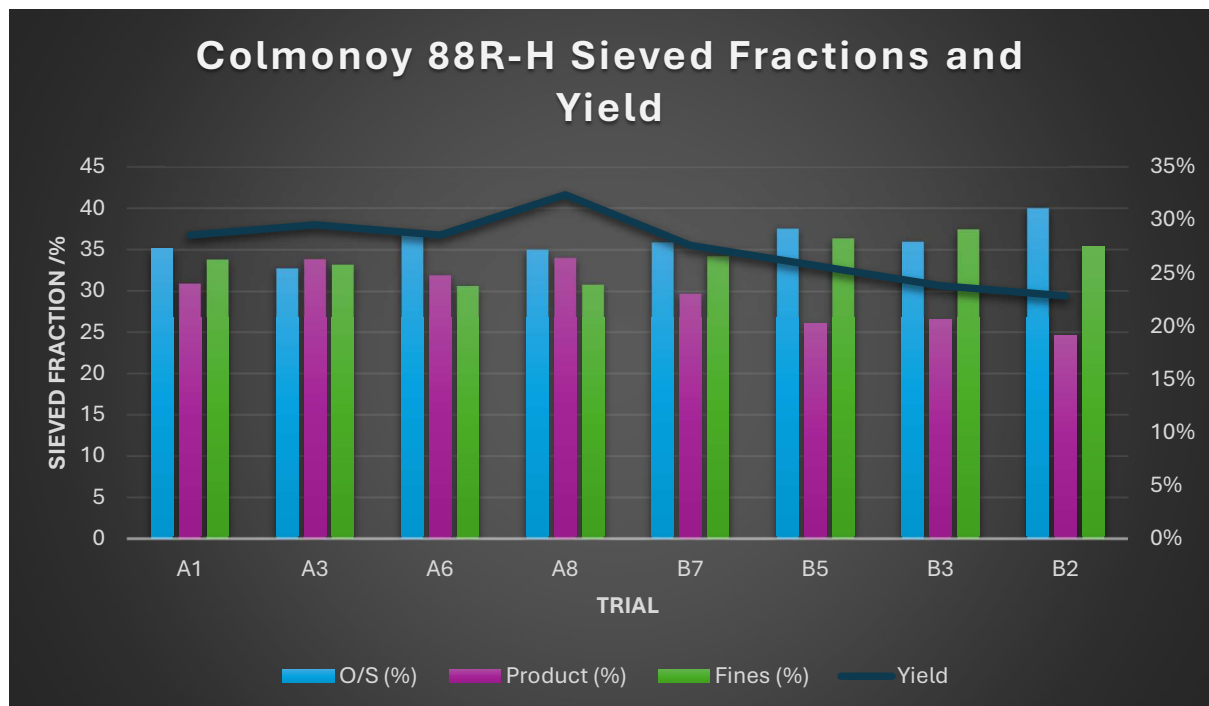


Figure 44 - Summary of Trial Results

Figure 44 shows the results from the trials which shows the percentage of waste (O/S & fines) along with the product vs the yield from the trial. It is clear to see from this data that the trial A8 had the best performance, as it demonstrated the highest yield and a right first time pass. This was primarily attributed to the retention of product, as opposed to losing material to fines or oversize fractions.

The particle size analysis for Trial A8 (shown in figure 45) revealed some product crossover in both the oversize and fines categories, but the overall performance was significantly better than in other trials. Within this industry there is a great challenge to obtain high yields and unfortunately, there is significant waste from this process route. This is due to the inefficiencies in the atomising process, where the screening efficiency can only become higher if the atomised powder is favoured to the end specification. Although, it is crucial to maximise screening performance in order achieve as much yield from the inputted powder. These yields are still low compared to other industries, a jump from 22% to 31% yield will have massive advantages for the company, as profits will increase along with being more competitive in the market to attract more business to further improve the bottom line. While Trial A3 retained more product, it was out of specification, requiring rework to meet the defined criteria, which would inevitably reduce the yield. The full particle size analysis from each trial can be found in appendices E to K.

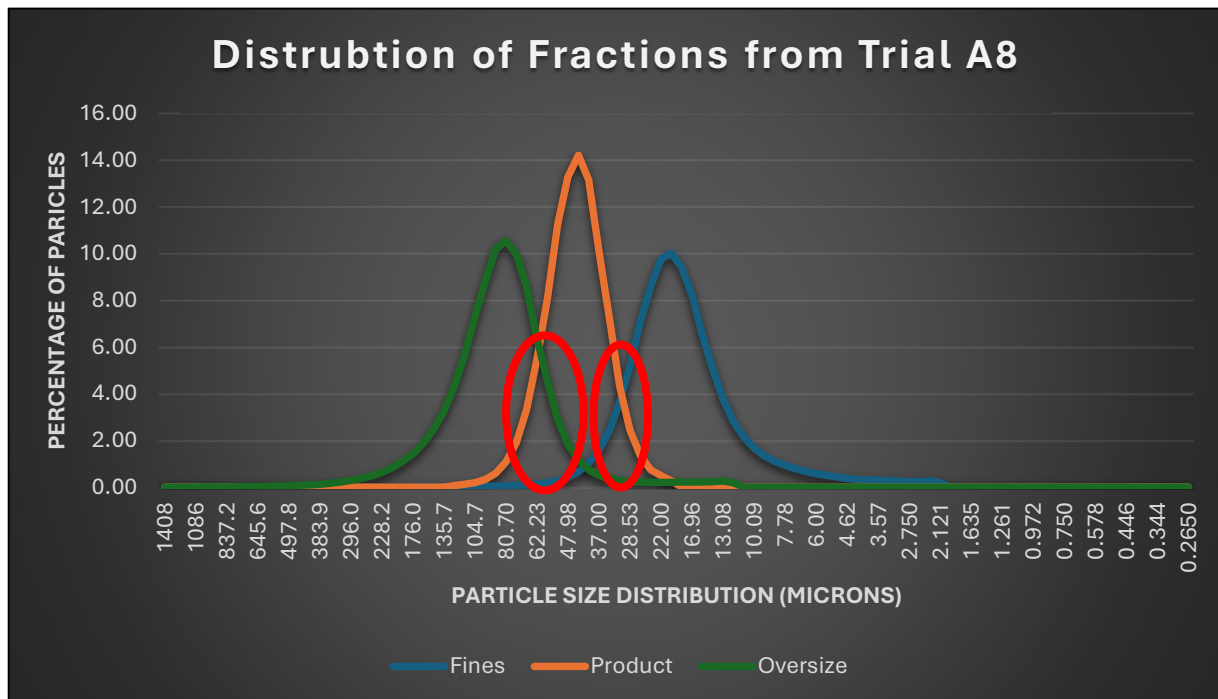


Figure 45 - Trial A8 PSD

6.5. Screening Efficiency

As shown in figure 44 trials A3 and A8 were the most efficient, both achieving a screening efficiency of 58%. Figure 46 shows how the screening efficiency was calculated based on the potential product yield in Trial A8, including the percentage of product and fines. The detailed calculations for all trials are provided in appendices L to R, with the lowest efficiency recorded in Trial B2 (43%). These trials underscore the importance of optimising screener setup to improve yields, particularly in metal powder screening processes, especially as the current screening system at Wall Colmonoy is at 46% which would mean an improvement of 12%.

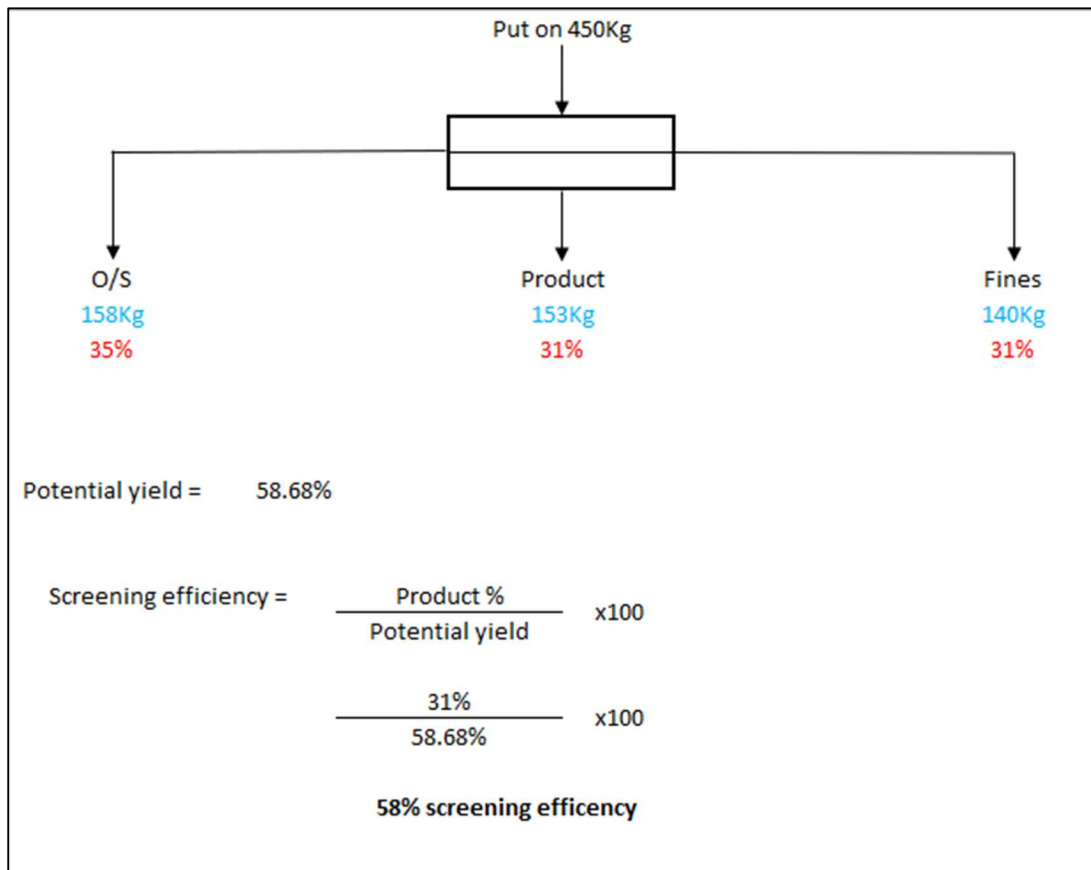


Figure 46 – A8 Screening Efficiency

6.6. Yield Calculations

The yield was calculated by the percentage of product within the product hopper that met specification on a right-first-time pass. The highest yield from the optimisation trials was 31%, achieved in Trial A8. This represents a 9% improvement in yield, corresponding to a 41% relative improvement which has been derived from by using equation 3.

$$\text{Relative Change} = \frac{\text{Final Value} - \text{Initial Value}}{\text{Initial Value}} \times 100$$

Equation 3 - Relative Change Equation

6.7. Upscaling Throughput Trials

Based on the positive results shown in the first trial, the plan was to run a series of products with the optimised setup shown in A8. The aim was to increase throughput and yield on the products as well as achieving a right first-time pass. These trials went for a duration of several months, screening a total of 58,000kg across all 11 products. This data was then compared to all screening performance going back to 2012.

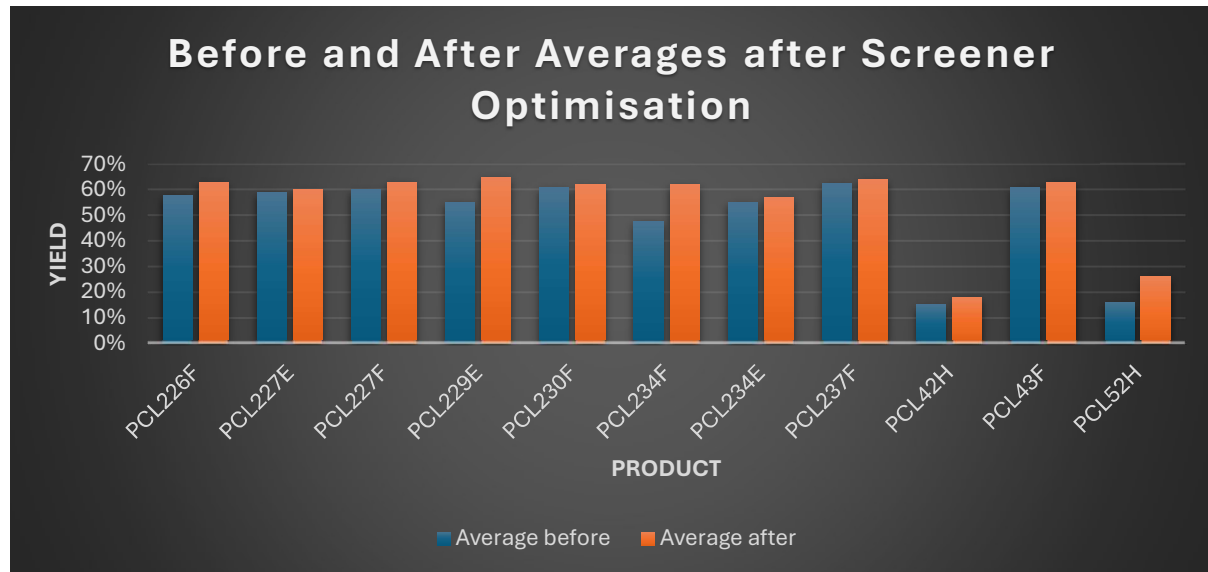


Figure 47 - RF Optimisation Graph

The graph shown in figure 47 shows the results of the trial where yield is up on all products as well as having right first-time success. Table 5 demonstrates these improvements in absolute and relative form. Due to chemistry composition, some products only had an absolute improvement of 1% where some products saw up to 14% improvements. From an overall average, the current screening method offers 22% while this new screening technology has the potential to increase to 31% on average across Wall Colmonoy's product line.

Material	Average before	Average after	Abs increase	Relative increase
PCL226F	58%	63%	5%	9%
PCL227E	59%	60%	1%	2%
PCL227F	60%	63%	3%	5%
PCL229E	55%	65%	10%	18%
PCL230F	61%	62%	1%	2%
PCL234F	48%	62%	14%	30%
PCL234E	55%	57%	2%	4%
PCL237F	63%	64%	2%	2%
PCL42H	15%	18%	3%	20%
PCL43F	61%	63%	2%	3%
PCL52H	16%	26%	10%	64%

Table 5 – Yield Increase Using Russel Finex Screener

7. Air Classification

For air classification this section provides analysis of three distinct trials. The goal of these trials was to evaluate performance across various parameters including, particle size distribution, flow rates, and yield efficiencies, to aid in the establishment of the most efficient setup for screening atomised metal powder containing super fines. After each trial, a sample is taken from the product and analysed using laser diffraction. The analysis is to evaluate how much of the $<20\mu\text{m}$ particles are not being classified and being carried over into the product hopper, after each adjustment is made. Each setup adjustment will result in varying screening efficiency with the goal to reduce this carry over to sub 1%. The loss in weight feeder will be utilised to run the required material through the classifier at the set feed rate. When adjusting the RPM for the screw and motor speed, a tachometer will be used to measure the speed of the motors. To adjust these speeds, an inverter will be utilised where frequency will be adjusted until the required RPM is achieved.

7.1. Experimental Setup

British Rema, a supplier of air classifier systems, utilised the technology for these trials. Several settings were adjusted varying the screw speed, rotor speed, and flow rates to determine optimal performance for separating particles at different size distributions, shown in point 10 and 11 in figure 48 respectively. These configurations aim to optimise yields and reduce the presence of fine particles ($<20\mu\text{m}$) in the coarse fraction. Each setup was recorded for its mass throughput, time taken, and percentage of $<20\mu\text{m}$ particles in the coarse mass.

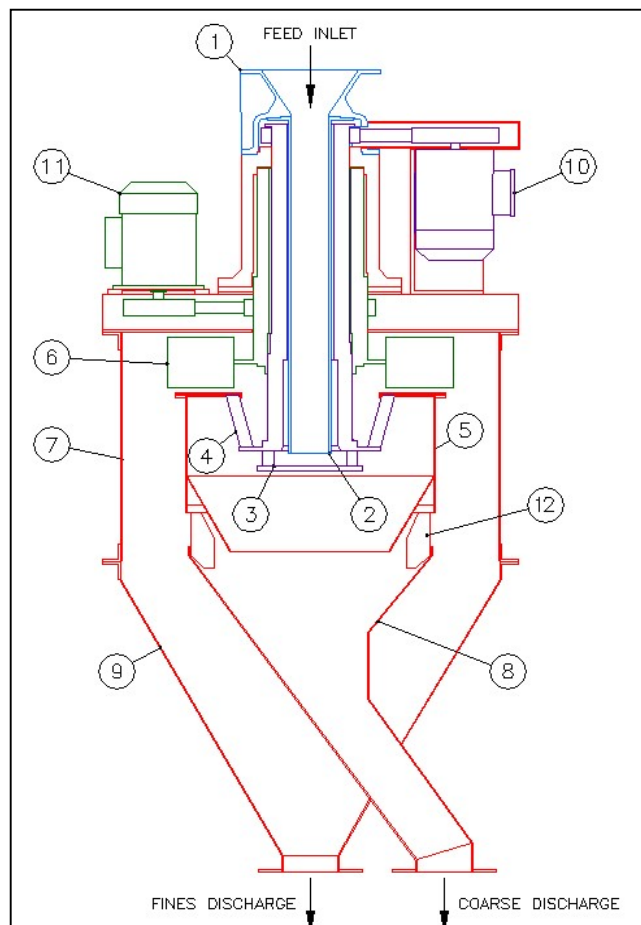


Figure 48 - Schematic of TD100

7.2. Results of Screw Rate Variation

In Trial 1 (table 6), the focus was on varying screw speeds (0 to 40 RPM) to measure the effects on the flow rate and the percentage of sub-20 μ m particles in the coarse fraction. The rotor speed was set to the manufacturers recommendations of 500 RPM and the throughput rate was set to 200kg/hr as an expected achievable. At lower screw rates (below 15 RPM), the sub-20 μ m percentages were high, ranging from 7% to 30%, meaning the screw was rotating too slow to effectively remove the required particle size. However, at higher screw rates (above 25RPM), the sub-20 μ m percentages increased significantly, reaching 18%-25%. Again, this indicates the screw is running too fast to effectively remove the required particle size distribution. The best result was observed in Run 1D, which achieved a screw rate of 20RPM with a sub-20 μ m value of 5%. While this run offers a good balance between throughput and quality, this is still too high for product carry over.

Run	Feed (kg)	Screw Speed (RPM)	Rotor Speed (RPM)	Flow Rate (kg/hr)	Sub -20 μ m in Coarse (%)
1A	5	5	500	200	30%
1B	5	10	500	200	22%
1C	5	15	500	200	8%
1D	5	20	500	200	5%
1E	5	25	500	200	12%
1F	5	30	500	200	18%
1G	5	40	500	200	25%

Table 6 - Trial 1 – Screw Speed

In conjunction with the results in Table 6, the screening efficiency of each trial is based on the carryover of particles into the +20 μ m band. The trend follows these results where the screening efficiency in table 7 ranges between 70% and 95%, where trial 1D has the highest screening efficiency due to the least amount of carry over.

Run	Sub -20 μ m in Coarse (%)	Screening Efficiency
1A	30%	70%
1B	22%	78%
1C	14%	86%
1D	5%	95%
1E	12%	88%
1F	18%	82%
1G	25%	75%

Table 7 – Screening Efficiency Trial 1

7.3. Results of Rotor Speed Variation

Trial 2 (table 8) explored the effect of rotor speeds (50-500 RPM) while maintaining a consistent flow rate of around 200 kg/hr and using the optimum screw rate of 20RPM. The sub-20µm percentages ranged from 2% to 12%, with higher rotor speeds (300-500 RPM) generally yielding better results. The best performance was observed in Run 2G, which had a screw rate of 400RPM and a sub-20µm percentage of 2%. The higher velocity from the rotor speed positively impacts the process as it suggests a higher centrifugal force is needed to effectively have particle separation. However, this still needs adequate balance. This setup further balanced throughput and quality, making it the optimal configuration in this trial. This is still outside the desirable product over percentage which is a target of less than 1%.

Run	Feed (kg)	Screw Speed (RPM)	Rotor Speed (RPM)	Flow Rate (kg/hr)	Sub -20µm in Coarse
2A	5	20	50	200	12%
2B	5	20	150	200	11%
2C	5	20	200	200	9%
2D	5	20	250	200	7%
2E	5	20	300	200	5%
2F	5	20	350	200	4%
2G	5	20	400	200	2%
2H	5	20	450	200	5%
2I	5	20	500	200	6%

Table 8 - Trial 2 – Rotor Speed

The screening efficiency was calculated similarly to the first trial. This time there was less range between the results which saw the screening efficiency be between 88% to 98%. As per table 9 the lowest efficiency was seen in 2A while the highest screening efficiency was in 2G.

Run	Sub -20µm in Coarse	Screening Efficiency
2A	12%	88%
2B	11%	89%
2C	9%	91%
2D	7%	93%
2E	5%	95%
2F	4%	96%
2G	2%	98%
2H	5%	95%
2I	6%	94%

Table 9 - Screening Efficiency Trial 2

7.4. Results of Throughput

Trial 3 (table 10) was the final trial which focused on the impact of throughput rate ranging from 50kg/hr – 500kg/hr and the impact on sub-20µm levels, which saw a range of carryover from 0.5% to 13%. From the previous trials, the screw and rotor speed were set to the optimum values of 20RPM and 400RPM respectively. The best result was observed in Run 3G, where 500kg/hr produced the lowest sub-20µm value of 0.5%. A slightly higher sub-20µm percentage of 0.9% and 1.4% was observed in Run 3F and 3E respectively, where the throughput rates were 450kg/hr and 300kg/hr. The influence of feed rate showed that a higher feed rate positively impacts throughput.

Run	Feed (kg)	Screw Speed (RPM)	Rotor Speed (RPM)	Flow Rate (kg/hr)	Sub -20µm in Coarse
3A	5	20	400	50	13.0%
3B	5	20	400	100	8.0%
3C	5	20	400	150	5.0%
3D	5	20	400	200	2.0%
3E	5	20	400	300	1.4%
3F	5	20	400	450	0.9%
3G	5	20	400	500	0.5%

Table 10 - Trial 3 – Feed Rate

Following the same principles from the two data sets, the efficiency from this data set had an efficiency between 87% and 99.5%, as seen in table 11. These trials achieved the highest efficiency rate (99.5%) seen, due to the optimisation progress made in the previous trials. The latter setup from these trials demonstrates an excellent balance of throughput and quality, which aid in the increase of right-first time rates, which ultimately increases the bottom line.

Run	Sub -20µm in Coarse	Screening Efficiency
3A	13%	87%
3B	8%	92%
3C	5%	95%
3D	2%	98%
3E	1%	98.6%
3F	1%	99.1%
3G	1%	99.5%

Table 11 - Screening Efficiency Trial 3

7.5. Particle Size Distribution

The results show a clear difference between air classification and the other screening techniques seen. This classification demonstrated a much finer distribution of particles in the mid-sized ranges (e.g., 90–125 μm). This indicates that while air classification offers better separation for finer particles, it struggles to separate at coarse bands. In the realms of the desire for finer particles, this technology would be sufficient. However, where there is a need for a range of PSD bands, this technology would be unfavourable. Thus, there could be a solution where two technologies are integrated to maximise performance.

7.6. Best Overall Setup

The results of the parametric study provide insights into the effect of rotor speed, screw speed, and throughput on the mass of coarse particles recovered, and the amount of fine material present in the coarse fraction.

Among all of the trials, the best overall configuration was observed in Trial 3, specifically Runs 3E, 3F, and 3G. These setups achieved a screening efficiency of over 98.5% with sub-20 μm values of 0.5% to 1.4%, representing the ideal balance between particle quality and throughput. This performance was achieved with a rotor speed of 400 RPM, a screw speed of 20RPM and throughputs between 300kg/hr and 500kg/hr, making it the most optimal setup across all conditions tested. Thus, it would be recommended to use 500kg/hr for optimal results.

7.7. Theory vs Actual Performance

This section explores the discrepancies between theoretical predictions and actual performance outcomes in the context of screening technologies for nickel and cobalt-based alloy production. By comparing expected efficiencies, yields, and throughput with empirical data collected from trials, the analysis highlights the limitations of theoretical models and identifies factors contributing to deviations. Understanding these discrepancies is critical for refining predictive models, improving operational performance, and ensuring that implemented solutions align with real-world manufacturing demands. This comparison not only validates the study's findings but also informs recommendations for future process optimisation.

7.7.1. Screw Speed

The results showed that the screw speed has a major impact on the classification system. The lowest carryover achieved was 5% at a screw speed of 20RPM, and the results around this screw rate were consistent. The theory suggested that the higher the screw rate the less efficient the method is. Which has been proved from these trials.

7.7.2. Rotor Speed

In the trials conducted the outcomes showed the best effects were seen at 400RPM, which resulted in the least amount of -20 μ m in the +20 μ m bracket. This proves the theory as the results expected are similar to what was observed.

7.7.3. Throughput

The trial data proved this, as at low throughput speeds (150kg/hr or less) there was a large degree of carry over (up to 13%). Whereas at higher throughput speeds, 300kg/hr plus, there was the minimum carry over (achieving 0.5% as the best).

8. Long Term Plan

The rapid development of advanced manufacturing (AM) technologies, particularly in additive manufacturing and medical applications, has led to increased demand for high-quality fine powders with narrow particle size distributions. Powders with particle sizes below 25 μm are critical for AM applications, where fine powder feeds result in better surface finishes, precision in printed parts, and for medical-grade materials that require exceptional purity and consistency. However, producing fine-grade powders that meet these exacting specifications presents significant challenges, particularly in achieving optimal throughput, yield, and right-first time (RFT) quality in production. Ultimately, the bottom line of an organisation depends on these factors.

Current industrial screening technologies, including vibratory screening and air classification, have distinct strengths and limitations. Vibratory screening is effective for separating particles within a certain range but struggles with fine particles below 25 μm , due to screen blinding and throughput limitations. Air classification, on the other hand, excels at separating fine powders, but often results in lower yields, particularly when high throughput is required. This paper presents a justification for the combined use of air classification and vibratory screening to meet the demands of high-throughput production, while optimising yield and RFT for fine powders, particularly those below 25 μm , which are crucial for the future of AM and medical use.

8.1. Importance of Fine Grade Powders

Achieving a consistent supply of fine powders, however, presents challenges in terms of particle size distribution (PSD) and process efficiency. Fine particles tend to agglomerate and clog screens, leading to lower throughput and reduced yields. Inconsistent particle sizes can negatively affect the flow properties of powders, which are crucial for AM feedstock, and can lead to defects in both AM and medical components. Hence, there is a need for more advanced and integrated screening systems that can effectively manage these issues, while maintaining high throughput and ensuring quality.

8.2. Limitations of Screening Technologies

This section provides a critical analysis of the limitations inherent in rotary screening, vibratory screening, and air classification technologies as applied to the production of nickel and cobalt based alloys. While each technology offers distinct advantages, the performance is often constrained by specific operational and material challenges, such as mesh blinding, scalability

issues, and diminished efficiency for ultra fine particles. By identifying these limitations, this section highlights the gaps in current methodologies and sets the stage for exploring hybrid or innovative solutions that can overcome these constraints. The insights gained here are pivotal for aligning screening technologies with the evolving demands of advanced manufacturing processes.

8.2.1. Vibratory Screening

Vibratory screening is widely used in powder processing due to its mechanical simplicity, robustness, and ability to handle large volumes of material. By using vibrating motion, particles are forced through screens of varying sizes to achieve separation. However, vibratory screening faces several limitations when handling fine powders below 25 μm . Screen blinding poses a significant challenge in the screening of fine powders, as particles often clog mesh openings, reducing overall efficiency and necessitating frequent maintenance. Whereas, in the Russell Finex trial the use of an ultrasonic mesh was able to reduce this pegging.

Throughput limitations also affect vibratory screens, as finer particles resist passing through smaller mesh sizes, thereby reducing the effective throughput. This shows that the life of the screen is limited and effects the efficiency of the screener. As Russell Finex offer the ultrasonic sieve system, it prolongs the life of the screen and ensures the efficiency of the screen is consistent.

In terms of yield, both vibratory screening methods proved better yield results over the conventional locker route. However, the Russell Finex route proved more consistent results in terms of efficiency and throughput.

8.2.2. Air Classification

Air classification offers a solution to many of the challenges faced by vibratory screening when processing fine powders. By using an air stream to separate particles based on the aerodynamic properties, air classifiers efficiently sort fine powders without the need for physical screens. The British Rema air classifier demonstrated its capability to separate fine particles. The classifier was able to effectively remove fine particles ($\sim 20\mu\text{m}$) with minimal product carry over, achieving over 99% screening efficiencies. Due to the separation being achieved via air flow, there is no risk of screen clogging.

Air classification alone, however, struggles with low throughput. The British Rema trials (with 50 kg/h feed rates) produced too much product carry over. However, at higher feed rates (500kg/hr) the classification was most efficient.

8.3. Justification for Combining Air Classification and Vibratory Screening

To address the limitations of each technology and capitalise on strengths, a combined system incorporating both vibratory screening and air classification offers a compelling solution for fine powder processing. Such a system would be capable of achieving the desired throughput, yield, and RFT rates, especially for the sub-25 μm powders required in AM and medical applications. Stakeholders, both internal and external, played a key role in the success of the project. Internal stakeholders included the CEO, managers, and employees, while external stakeholders comprised of suppliers, customers, and shareholders. A stakeholder mapping process was conducted to identify and prioritise key stakeholders, particularly those who could offer the most support during the trials. For any change of process, the stakeholders all must sign the documentation, which includes the engineer, engineering manager, operations supervisor, department manager, SHE manager and the operational director. When it comes to financial spend, all the above are required plus the managing director and president of the organisation.

8.3.1. Enhanced Throughput

A combined setup can achieve higher throughput without sacrificing fine particle separation. Air classification could be used as a pre-classification stage, removing finer particles before they enter the vibratory screener. This would reduce the load on the vibratory screener, allowing it to operate more efficiently at the desired cut points while maintaining higher throughput. For instance, in the air classification trials, higher feed rates of up to 300 kg/h were achieved, though fines were still present in the coarser fractions. Combining air classification would allow for better separation of fines while maintaining throughput. This would allow better control over particle distribution, indicating the potential for improved performance if combined with vibratory screening.

8.3.2. Improved Yield

A combined system would allow better yield management by minimising material loss and maximising recovery of waste particles. Vibratory screens handle the bulk of the material, allowing the air classifier to focus on fine particle separation. Trials on the air classifier showed the impact of different rotor and screw speeds on the fine particle yield. For example, trial 3 with a rotor speed of 400 RPM yielded 0.5% fines $<20\ \mu\text{m}$ in the coarse fraction, showing the potential for precise adjustments. This fine control, as a pre-screening step, for vibratory screening, would enhance yield by effectively managing coarse and fine particle separation.

8.3.3. Right-First Time (RFT) Improvements

Combining air classification with vibratory screening would lead to significant RFT improvements by ensuring that only the desired particle sizes pass through the system. Current right first time values are 51% and the aim is to get 80% based on the trials completed. This increase in RFT would increase the profitability of the organisation and has the potential to have more business. By increasing the right first time rates by 31% this would be before any new business which could result in significant revenue increase by around £132k per year.

8.3.4. Optimised Fine Powder Processing

For AM and medical applications requiring powders below 25 μm , a combined approach offers the best of both worlds. Air classification provides efficient separation of -20 μm particles when the parameters are set at rotor speed of 400RPM, screw speed of 20RPM, and a throughput rate of 150kg/hr, which achieves up to 99.5% efficiency. This ensures that only coarse (+20 μm) particles go into the vibratory screener. Based on the trials, the optimum set up for vibratory screening is using an ultrasonic mesh, setting the lead angle to 90°, the amplitude G:G, and the feed rate at 300kg/hr to give 58% screening efficiency. Based on the data, this has the potential to aid in a 41% relative improvement in screening operations at WCL.

The combination of air classification and vibratory screening offers a robust solution for the high-throughput production of fine powders, particularly those below 25 μm . This hybrid approach maximises yield, improves throughput, and enhances RFT performance by leveraging the strengths of both technologies. As AM and medical applications continue to demand finer powders, the integration of these technologies will be critical for meeting the stringent requirements of these industries, ensuring consistent, high-quality powder production for the future.

9. Implementation

The implementation of a combined air classification and vibratory screening system necessitates a comprehensive and systematic approach to facilitate seamless integration within the existing production environment. The primary objectives of the installation are to enhance throughput, improve yield, and preserve product quality, particularly for fine powders below 25 µm. This section details the key aspects of the implementation phase, emphasising project documentation, Management of Change (MOC), and Failure Modes and Effects Analysis (FMEA). These elements are essential for ensuring the efficient operation of the new system, mitigating potential risks, and achieving the operational objectives defined in the project scope.

Before using resources to implement key safety documentation, the project needs approval from the relevant stakeholders. This justification document outlines the current situation within the process, the goals of the project, consideration to alternatives to the proposed project, before going through the financials of the project, as shown in figure 49 .

 WALLCOLMONOY	
Capital Expenditure Justification	
Project Name	Powder Processing Cell
Purpose	
Describe the current situation	
Describe what the project will achieve	
Describe any alternatives to the project	
Describe what would happen if the project didn't happen	
Result of Net Present Value calculation	

Figure 49 - CapEx Justification Template

9.1. Project Documentation

Project documentation is the foundation of a well-organised installation process, providing clear guidelines and ensuring alignment between stakeholders throughout the project. The first key document is the Scope of Work (SoW), which clearly defines the objectives of installing the air classification and vibratory screening system. This document outlines the intended improvements in process performance, including the integration of the new equipment, throughput expectations, and particle size distribution targets. For example, the vibratory screening system is expected to handle feed rates of approximately 300 kg/hr, while the air classifier is expected to manage rates of 500 kg/hr. The SoW should also include the expected improvements in fine particle separation, particularly for sub-25 µm powders used in advanced manufacturing and medical applications.

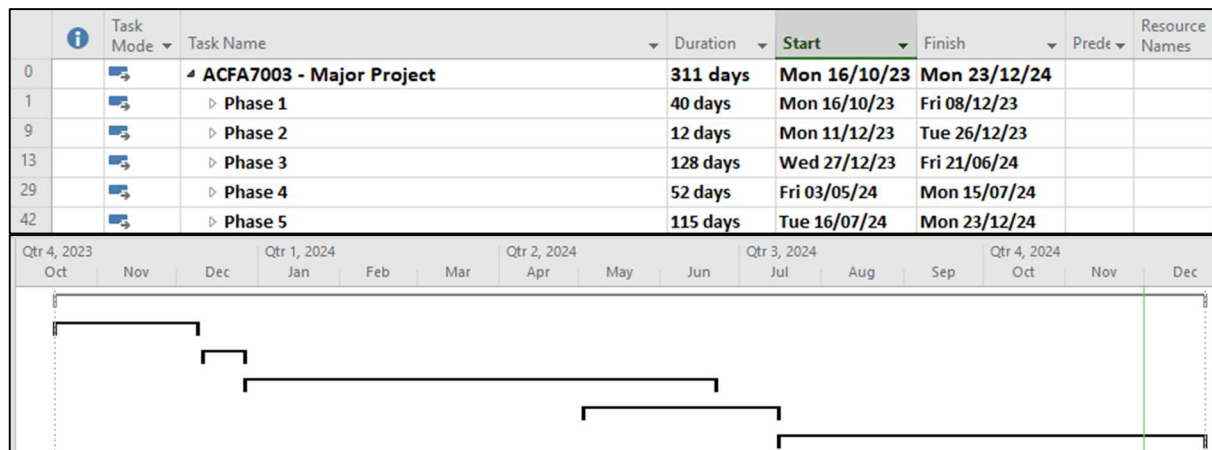


Figure 50 - Gantt Chart for this project

Another essential component of the project documentation is the specification of the equipment. This includes the technical details such as power requirements, equipment dimensions, and process flow diagrams, that show the integration points between the air classification and vibratory screening systems. Proper documentation ensures that all team members understand the physical layout and technical capabilities of the new equipment. For instance, the vibratory screening trials and air classification trials highlighted the importance of specific operating parameters, like rotor speeds of 500 RPM, screw rates of 20RPM, along with trial A8 from the Russell Finex trials. A well-documented installation plan, detailing each phase from site preparation to commissioning, will provide a clear roadmap for achieving installation success.

A Gantt chart shown in figure 50 outlines the time period for this project which spans over a 1 year period and covers research, trials, and installation.

CAPEX Project Spend Control Document

Project Name	New Powder Production Line
CAPEX Number	CP1242
Project Manager	Gavin John
Department	Alloy Products
CAPEX Approved Cost	£582,588

Item	Company	Approved Cost
1. Structural Works		£18,000.00
1.1 Structural Calculations	Thomas Davies Associates	£2,000.00
1.2 Mezzanine Structure	Thomas Davies Associates	£16,000.00
2. Screening Equipment		£434,625.00
2.1 Vibratory Screener	Russell Finex	£20,000.00
2.2 Atex rated air classifier	British Rema	£405,850.00
2.3 Screen deck lifter	Russell Finex	£8,775.00
3. Feed Rate Control		£17,000.00
3.1 Air Conveyor System	Volkman	£14,000.00
3.2 Loss in weight feeders	Various	£3,000.00
4. Miscellaneous		£60,000.00
4.1 Extraction Unit	Nedermann	£13,000.00
4.2 Weighing Scales	Applied Weighing	£10,000.00
4.3 Consumables	Various	£8,000.00
4.4 Installation	Various	£4,000.00
4.5 Control System	Hornbill	£25,000.00

Figure 51 - Outline Spend

Additionally, the project documentation must include detailed process flow diagrams (PFDs) and piping and instrumentation diagrams (P&IDs). These diagrams are critical for visualising the movement of materials, and understanding how the system will operate once integrated. By mapping out the equipment's interactions with other processes, these documents help identify critical control points, which will be crucial for maintaining optimal particle separation and process throughput. Monitoring systems will need to be installed to ensure the air classifier consistently separates the required fines from the bulk material, maintaining a balance between coarse and fine fractions.

Figure 51 is a high level budget management template which accounts for spends for different activities in the project.

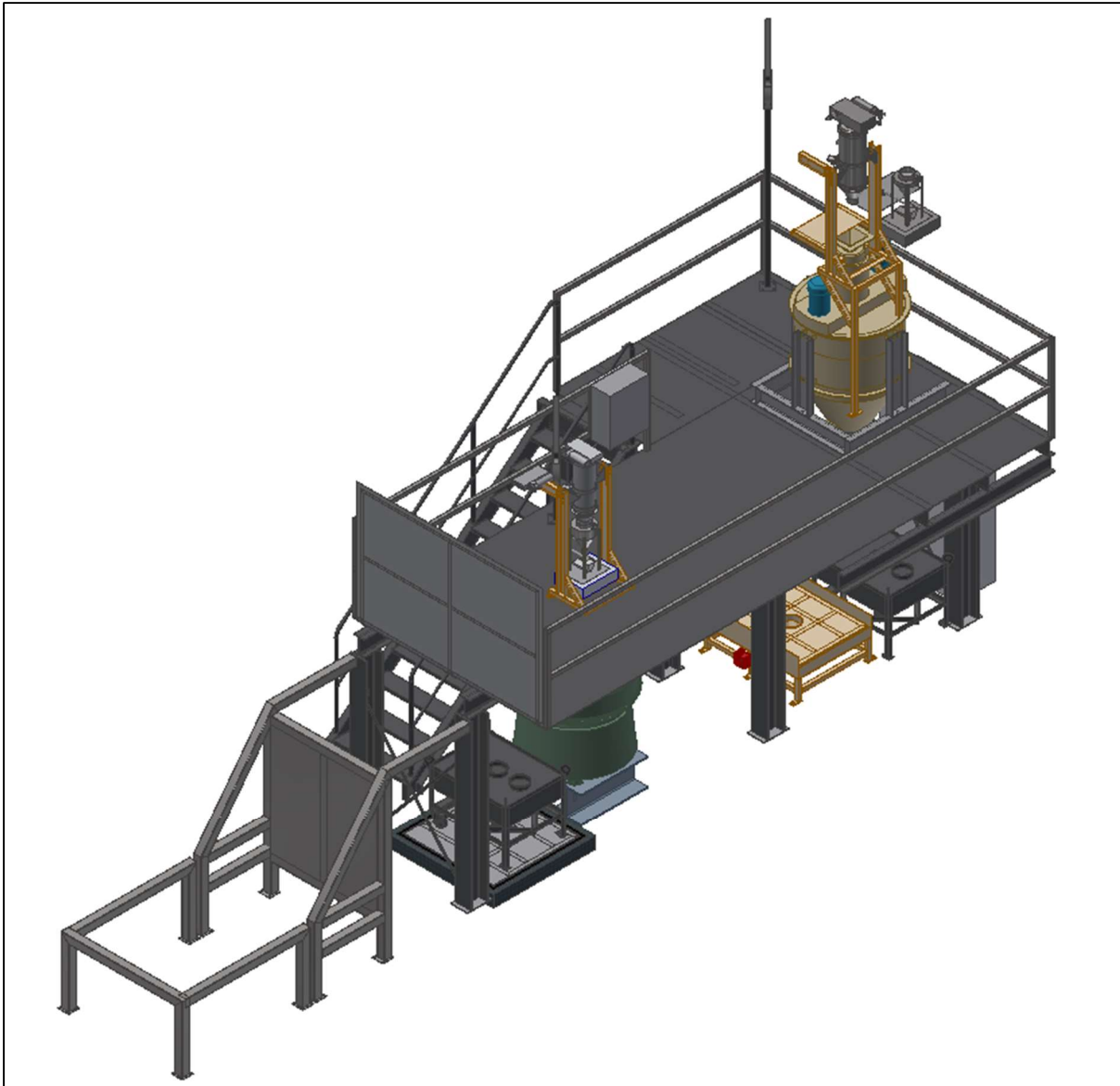


Figure 52 - Layout Drawings of New Production Line

Figure 52 shows a CAD package showing the general arrangement for the layout of the combination system. By doing these layouts allow for issues to be highlighted in the design review (SMART factory) before installation to minimise issues past installation.

9.2. Management of Change (MOC)

Management of Change (MOC) is a structured process designed to evaluate the impacts of any modifications made to the existing production environment. The installation of new air classification and vibratory screening systems constitutes a significant change, and therefore, a formal MOC procedure must be followed to ensure a smooth transition. The first step in the MOC process is to identify the specific changes being introduced, such as the addition of air classification to the production line, which was previously based solely on rotary screening technology. This new process will impact material flow, equipment operation, and the handling of fine powders.

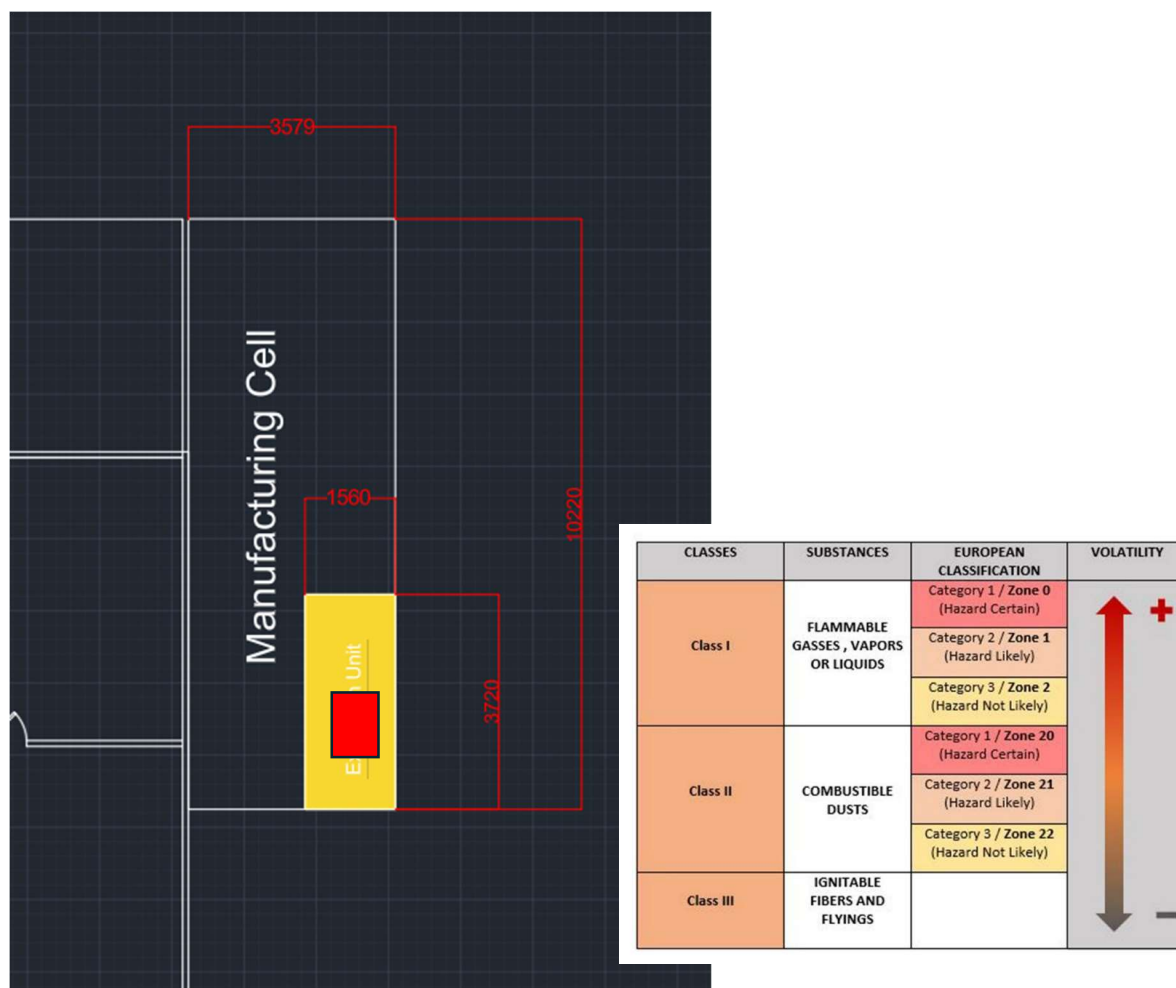


Figure 53 - Atex Zoning for the Extraction Unit

A comprehensive risk assessment must be conducted as part of the MOC process. This assessment will evaluate operational risks, such as downtime during installation and commissioning, as well as the potential for equipment underperformance or failure. Safety risks must also be considered, particularly those related to the introduction of mechanical motion, electrical components, and high-velocity airflow into the production area. The presence of sub-25 μm powders introduces additional safety concerns, such as dust explosion

hazards, which must be addressed through proper containment and ventilation systems. In addition, the risk assessment should consider the potential impact of the new system on product quality. As the risk poses an explosion, an ATEX rated extraction system was proposed complying with ATEX directive 99/92/EC Article 37 and The Dangerous Substances and Explosive Atmospheres Regulations 2002. Shown in figure 53 is a floor plan for the proposed manufacturing cell. Within this drawing the zoning of the area which would be a zone 21 is shown, as there is highly likely be an explosion within 10 and 1,000 hours, in the event of a failure in the system. As part of the regulations, clear signs will also have to be implemented to notify personnel of the rated zone, while the extraction unit itself is zone 20 which means there is a constant risk of explosion.

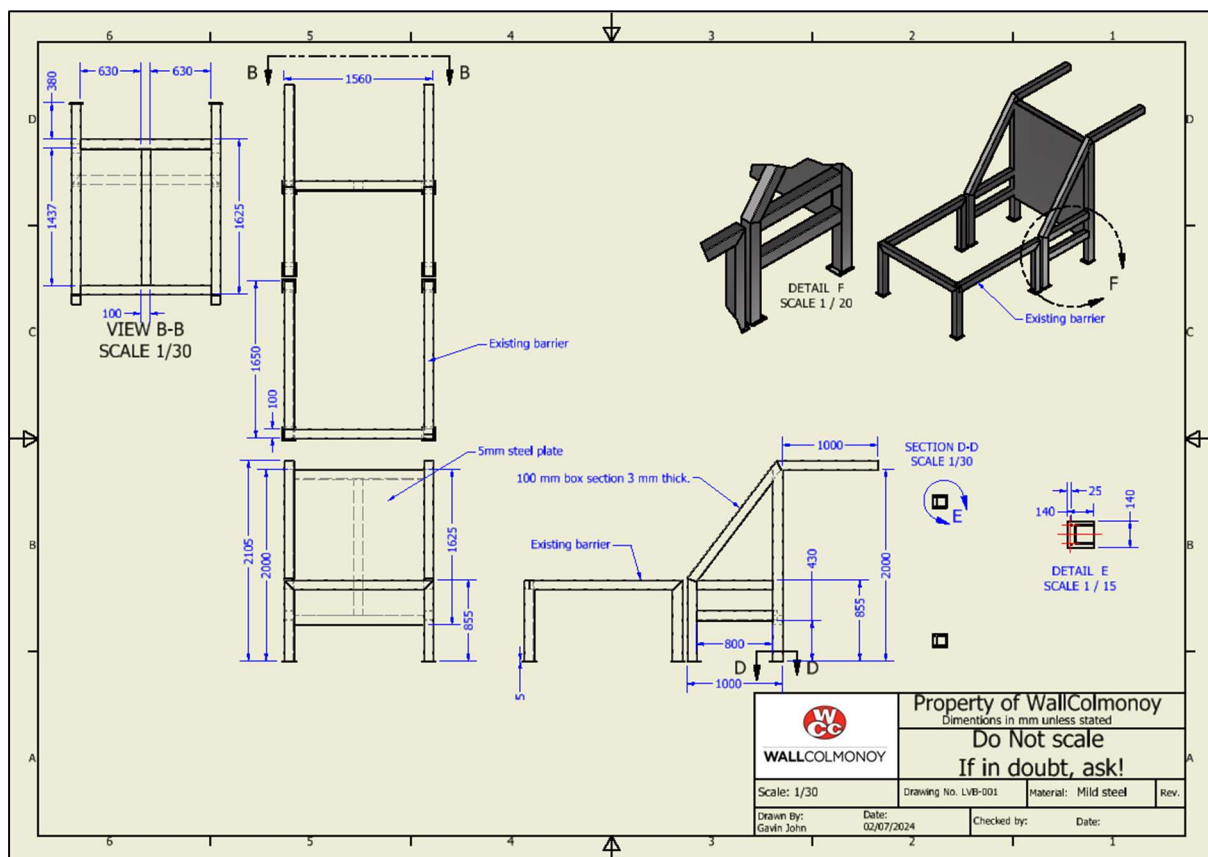


Figure 54 - Blast Barrier Manufacturing Drawing

The MOC review highlighted the need for blast protection so if an event took place, it would ensure the safety of all in the area. In figure 54 a concept design was created, and structural analysis was conducted based on the possible pressure being released from the unit (pressure). The extraction unit would be ATEX rated to IIC and would have an explosion vent on one side hence the barrier only required on one side. From this analysis, less than 0.5mm displacement is anticipated based on the construction of the framed barrier shown in figure 55.

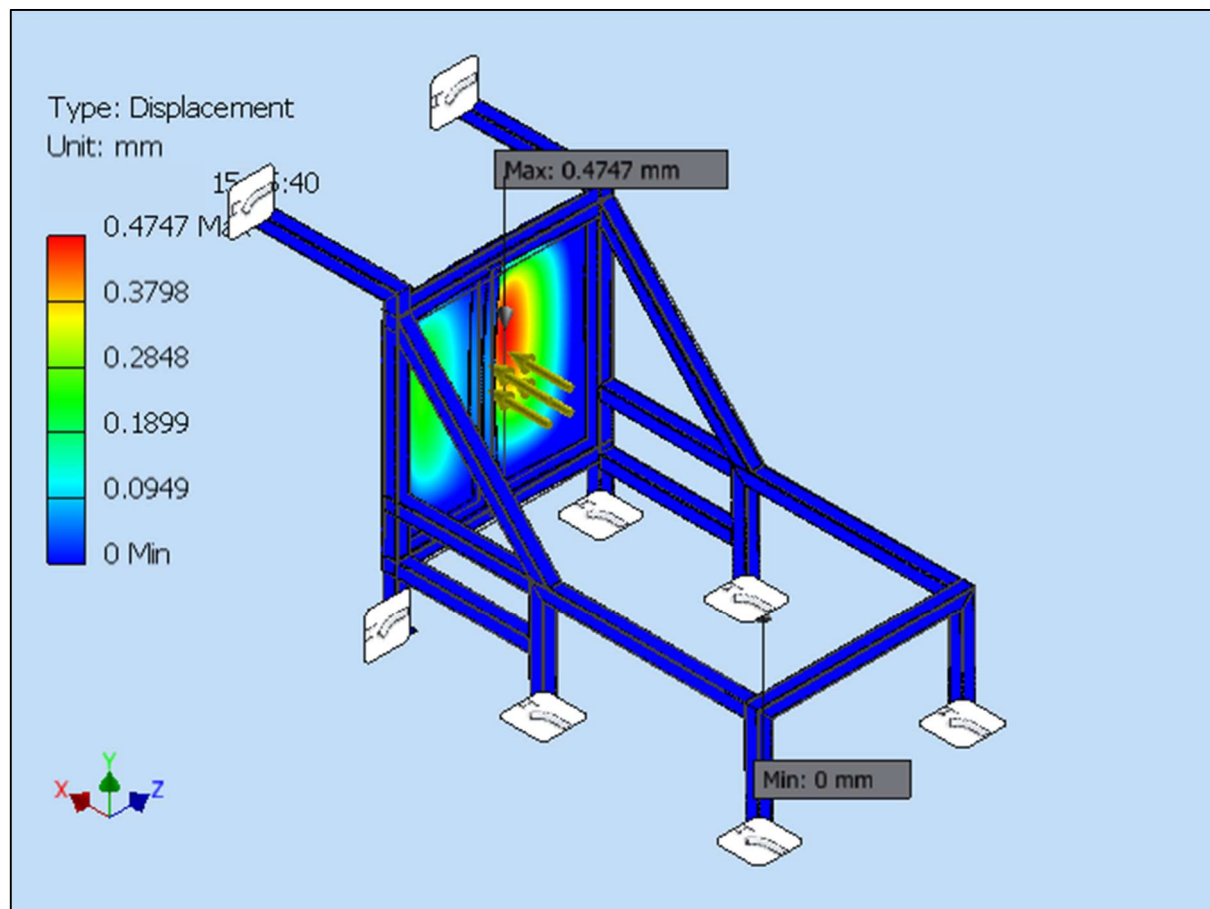


Figure 55 - Stress Analysis of Blast Frame

Once the risks have been identified, the MOC process moves into the approval phase, where all relevant stakeholders, including production managers, engineers, and safety officers, must sign off on the proposed changes. This ensures that all potential risks have been adequately addressed and that appropriate mitigation strategies are in place before the new system is installed. After approvals are obtained, the MOC process will also involve extensive communication and training. Operators, maintenance personnel, and quality control teams must be educated on the new system's operation, including how to monitor critical parameters like rotor speed and feed rates. Given the complexity of the combined system, clear standard operating procedures (SOPs) must be developed to guide the operation and maintenance of the equipment.

Adherence to BSI (British Standards Institution) and EN (European Norm) standards is critical when implementing new systems such as air classification and vibratory screening technologies. These standards, including BS EN 14181 for quality assurance of automated measuring systems and BS EN 16770 for equipment safety, ensure that the design, installation, and operation of the equipment meet stringent safety, environmental, and performance benchmarks. Compliance with these standards not only reduces the risk of operational failure and safety incidents, but also facilitates the system's alignment with regulatory requirements and industry best practices. For instance, BS EN ISO 80079-36 and BS EN ISO 80079-37 are particularly relevant for managing explosion risks in environments handling fine powders. Implementing these standards provides a framework for designing safer production processes and demonstrates a commitment to quality and safety assurance.

 WALLCOLMONOY SURFACING ALLOYS	WALLCOLMONOY LTD. (UK) MATERIAL SAFETY DATA SHEET			
COLMONOY® Group 1b Nickel-based Alloy Powders	In accordance with REACH (EC) No. 1907/2006 Annex II, Amended Regulation 453/2010 Annex II MSDS Code 2001a Revision 00 Date 09/09/2015			
Section 1: Identification of the Substance/Mixture and of the Company/Undertaking				
<table border="1"> <tr> <td> 1.1 Product identifiers: COLMONOY® 12/50/11 COLMONOY® 27 COLMONOY® ST40 COLMONOY® 226 COLMONOY® 520 </td> <td> COLMONOY® 22 COLMONOY® 28 COLMONOY® CM42 COLMONOY® 227 COLMONOY® 901 </td> <td> COLMONOY® 25 COLMONOY® 29 COLMONOY® 225 COLMONOY® 228 COLMONOY® 1015 </td> </tr> </table>		1.1 Product identifiers: COLMONOY® 12/50/11 COLMONOY® 27 COLMONOY® ST40 COLMONOY® 226 COLMONOY® 520	COLMONOY® 22 COLMONOY® 28 COLMONOY® CM42 COLMONOY® 227 COLMONOY® 901	COLMONOY® 25 COLMONOY® 29 COLMONOY® 225 COLMONOY® 228 COLMONOY® 1015
1.1 Product identifiers: COLMONOY® 12/50/11 COLMONOY® 27 COLMONOY® ST40 COLMONOY® 226 COLMONOY® 520	COLMONOY® 22 COLMONOY® 28 COLMONOY® CM42 COLMONOY® 227 COLMONOY® 901	COLMONOY® 25 COLMONOY® 29 COLMONOY® 225 COLMONOY® 228 COLMONOY® 1015		
1.2 Relevant identified uses of the mixture: Nickel-based hard surfacing alloys for wear-resistant coating. For industrial use by professionals only.				
1.3 Company: Wall Colmonoy Ltd, Alloy Industrial Estate, Pontardawe, Swansea, SA8 4HL, United Kingdom				
Responsible Department: Quality Laboratory Telephone Number: +44(0)1792-862287 E-mail Address: sales@wallcolmonoy.co.uk				
1.4 Emergency Telephone: +44(0)1792-862287 (available 08.30-16.30 hours only)				
Section 2: Hazards Identification				
2.1 Classification of component substances in the mixture in accordance with Classification, Labelling and Packaging Regulation (EC) 1272/2008				
Hazard class Skin Sensitisation – Category 1 Carcinogenicity – Category 2 Specific Target Organ Toxicity, Repeated Exposure – Category 1 (respiratory system, kidney, liver) Aquatic toxicity, chronic – Category 3				
Hazard statement H317 – May cause an allergic skin reaction. H351 – Suspected of causing cancer. H372 – Causes damage to organs through prolonged or repeated inhalation. H412 – Harmful to aquatic life with long-lasting effects.				

Figure 56 - Example of MSDS

Figure 56 shows an example of an MSDS sheet for powders at WCL. These documents are pivotal safety documents as critical safety, storage, and disposal methods are described.

All newly installed equipment must bear the appropriate UKCA (UK Conformity Assessed) markings to signify compliance with essential health, safety, and environmental regulations.

These markings indicate that the equipment meets the requirements of applicable directives, such as the Machinery Directive 2006/42/EC and the ATEX Directive 2014/34/EU. For systems handling fine powders, the UKCA markings verify that the equipment has been designed to mitigate risks, such as dust explosions and mechanical failures. This also certifies inspections and approvals by regulatory bodies to enhance the credibility of the equipment. Ensuring that the equipment carries these markings is an integral part of the MOC process and underscores the organisation's adherence to legal and operational standards.

9.3. Failure Modes and Effects Analysis (FMEA)

Failure Modes and Effects Analysis (FMEA) is a critical tool for proactively identifying potential failure points within the air classification and vibratory screening system. The FMEA process helps ensure that the system operates reliably and consistently while mitigating risks related to equipment failure, process deviations, and human error, where a summary FMEA is shown in table 12. One potential failure mode involves the rotor in the air classifier. If the rotor speed falls below the optimal level, the efficiency of fine particle separation decreases, as evidenced by the trial data, where speeds below 400 RPM reduced the separation efficiency. This failure could lead to an increased proportion of fines in the coarse fraction, which would negatively impact product quality, particularly for applications requiring high precision in particle size distribution.

			PROCESS FAILURE MODE and EFFECTS ANALYSIS							Rev No		1
			PPC Process							Date		
Seq	Process step / Function	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes / Mechanisms of Failure	Current Process Controls (Preventive)	Occur	Current Process Controls (Detection)	Detect	R.P.N.	Recommended Actions	
1	Put hopper bin on stand and open sanders valve	Powder wont flow	Powder can't be processed	7	Powder is bridged in bin	None	6	Vibration device on hopper	2	84	No action required	
				7	Wet powder	Dry for 2 hours	6	None	3	126	Moisture test	
9	Powder transfer to Volkmann (VP1)	No powder transfer	Powder can't be processed	6	Hole in transfer pipe	Maintenan ce checks every month	5	Alarm System	2	60	No action required	
				6	Transfer pipe elongated	None	6	Alarm System	2	72	Review - combinati on of S and O	
		Low or no pressure on digital gauge	Powder can't be processed	6	Hole in transfer pipe	Maintenan ce checks every month	6	Pressure transducers & alarm system	2	72	Review - combinati on of S and O	
11	Powder transfer to vibratory feeder (VF1)	Powder wont transfer to vibratory feeder (VF1)	Powder can't be processed	6	Powder buffer hopper (BH1) blocked at outlet	None	5	Low feed rate indicated on HMI screen	2	60	Review - combinati on of S and O	
				7	Transfer sleeve split	None	7	Feed rate indicated on HMI screen	2	98	Review - combinati on of S and O	
		Transfer sleeve failure	Powder can't be processed	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combinati on of S and O	
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combinati on of S and O	
			Fugitive dust	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combinati on of S and O	

				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
			Damage to Vibratory feeder (VF1)	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
12	Vibratory feeder (VF1)	No material flowing	Powder can't be processed	6	Feeder Motor not working correctly	Maintenance checks every month	5	Feed rate indicated on HMI screen	2	60	Review - combination of S and O
13	Classifier (CL)	Classifier rotor not tuning	Powder can't be processed	5	Motor belt has broken	None	5	None	3	75	Review - combination of S and O
16	Fines bin	Leaking material	Fugitive dust	6	Extraction pipe not connected	None	6	Operator dependant	2	72	Review - combination of S and O
17	Product and oversize bin	Leaking material	Fugitive dust	6	Extraction not working	None	6	Operator dependant	2	72	Review - combination of S and O
19	Powder transfer to Volkmann (VP2)	No powder transfer	Powder can't be processed	6	Hole in transfer pipe	Maintenance checks every month	5	Alarm System	2	60	Review - combination of S and O
				6	Transfer pipe elongated	None	6	Alarm System	2	72	Review - combination of S and O
21	Powder transfer to vibratory feeder (VF2)	Powder wont transfer to vibratory feeder (VF2)	Powder can't be processed	6	Powder buffer hopper (BH2) blocked at outlet	None	5	Low feed rate indicated on HMI screen	2	60	Review - combination of S and O
				7	Transfer sleeve split	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
			Powder can't be processed	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
			Fugitive dust	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
			Damage to Vibratory feeder (VF2)	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
23	Oversize hopper	Leaking material	Fugitive dust	6	Extraction pipe not connected to Russell finex	None	6	Operator dependant	2	72	Review - combination of S and O
21	Product hopper	Leaking material	Fugitive dust	6	Extraction pipe not connected to Russel finex	None	6	Operator dependant	2	72	Review - combination of S and O

Table 12 - Summarised FMEA

Another potential failure mode is screen blinding within the vibratory screening system, which could result from improper cleaning or excessive moisture in the feed material. Screen blinding can reduce throughput and lead to inefficiencies in separating fine powders. For example, in the Russell Finex trials, where feed rates achieved 300kg/hr, maintaining optimal screen performance was crucial to ensuring that particle sizes above 53 μm were properly screened. Regular cleaning schedules and the implementation of anti-blinding technologies, such as ultrasonic devices, will help mitigate this failure mode.

Human error is also a significant factor that must be addressed in the FMEA. Incorrect equipment setup, failure to monitor key process variables, or improper handling of materials could lead to system failures and compromised product quality. To reduce the likelihood of human error, operators should receive thorough training on both the air classification and vibratory screening systems. Automating certain aspects of the process, such as feed rate control and rotor speed adjustments, will further minimise the risk of operator-induced errors. The full FMEA can be seen in appendix B where the majority of risks highlighted were in the low-risk range whereas only two were in the moderate risk category.

An FMEA is similar to a risk assessment as an RPN is generated by multiplying the severity by the occurrence and the detection. This assessment used a 0-10 ranking system for each category. The severity was based on low, medium and high risk, the full definitions are outlined in table 13.

Severity Rank				
Rank	Effect	Description	Definition (End User Effect)	Manufacturing Effect
10	Hazardous without Warning	Failure to meet safety and/or regulatory requirements.	Affects safe 'end user' operation and or involves noncompliance with government regulation without warning.	May endanger operator (machine or assembly) without warning
9	Hazardous with Warning		Affects safe 'end user' operation and or involves noncompliance with government regulation with warning.	May endanger operator (machine or assembly) with warning
8	Very High	Loss or degradation of primary function	Failure renders the product/unit/part inoperable or unfit for use.	100% of product may have to be scrapped. Line shutdown or stop ship.
7	High		Degradation of primary function. Fit for use operable but at a reduced level of performance.	A portion of the production run may have to be scrapped. Deviation forms primary process including decreased line speed or added manpower.
6	Moderate	Loss or degradation of secondary function	Failure results in a subsystem or partial malfunction of the product.	100% of production run may have to be reworked offline and accepted.
5	Low		Failure creates enough of a performance loss to cause the customer to complain.	A portion of the production run may have to be reworked offline and accepted.
4	Very Low	Annoyance	Failure can be overcome with modifications to the customer's process or product, but there is minor performance loss.	100% of production run may have to be reworked in station before it is processed
3	Minor		Failure would create a minor nuisance to the customer, but the customer can overcome it without performance loss.	A portion of the production run may have to be reworked in station before it is progressed.
2	Very Minor		Failure may not be readily apparent to the customer but would have minor effects on the customer's process or product.	Slight inconvenience to process, operation, or operator.
1	None	No effect	No discernible effect	No discernible effect

Table 13 - Severity Ranking

The occurrence was based on how likely an event would take place. Table 14 shows the relevance of each member.

Occurrence			
Rank	Probability of Failure	Description	%
10	Very High	>100 Per 1,000 (1 in 10)	10.00
9	High	50 Per 1,000 (1 in 20)	5.00
8		20 Per 1,000 (1 in 50)	2.00
7		10 Per 1,000 (1 in 100)	1.00
6	Moderate	2 Per 1,000 (1 in 500)	0.20
5		0.5 Per 1,000 (1 in 2,000)	0.05
4		0.1 Per 1,000 (1 in 10,000)	0.01
3	Low	0.1 Per 1,000 (1 in 10,000)	<0.01
2		< 0.001 Per 1,000 (1 in 1 million)	< .0001
1	Very Low	Failure is Eliminated	0.00

Table 14 - Occurrence Ranking

The Process Failure Mode and Effects Analysis (PFMEA) outlines a comprehensive range of current control methods employed to mitigate potential failure modes and the effects on the manufacturing process. These methods are categorised into two key types, preventive controls and detection controls, which ensure product quality and operational efficiency.

Preventive control methods are proactive measures designed to eliminate or minimise the likelihood of failure before it occurs. In the PFMEA, these include regular maintenance of machinery, process parameter checks, and the use of calibrated tools and equipment. For example, monitoring critical parameters such as feed rate, temperature, and screen tension in rotary or vibratory screening ensures consistent performance and prevents deviations that could lead to product quality issues. Additionally, standard operating procedures (SOPs) and operator training programs are included as preventive measures to enhance process reliability and reduce human error.

Detection controls focus on identifying defects or process deviations during or after the operation to prevent defective products from reaching customers, as shown in table 15. These controls include automated inspection systems, in-process sampling, and visual inspections performed by skilled operators. For instance, particle size distribution analysis and equipment alarms for detecting screen blinding or overload are critical detection methods listed in the PFMEA. These measures ensure that issues are promptly identified, enabling corrective actions to be implemented before the process continues.

Both types of control methods play a pivotal role in reducing the risk priority number (RPN) by addressing the severity, occurrence, and detectability of potential failures. The FMEA highlights the importance of regularly reviewing and optimising these controls to ensure they remain effective and aligned with process improvements and quality goals.

Detection						
Rank	Detection	Criteria	A	B	C	Definition
10	Almost Impossible	No detection opportunity			X	No current process control; Cannot detect or is not checked.
9	Very Unlikely	Current Controls will probably not detect			X	Failure mode and or error (Cause) is not easily detected (e.g., random audits).
8	Unlikely	Controls have poor chance of detection			X	Failure mode detection post-processing by operator through visual/tactile/audible means.
7	Very Low	Controls have poor chance of detection			X	Failure mode detection in-station by operator through visual/tactile/audible means or post processing through use of attribute gauging (go.nogo, manual torque check/clicker wrench etc.).
6	Low	Controls may detect		X	X	Failure mode detection post processing by operator through use of variable gauging or in-station by operator through use of attribute gauging (go.nogo, manual torque check/clicker wrench etc.).
5	Moderate	Controls may detect	X	X		Failure mode or Error (cause) detection in station by operator through use of variable gauging or by automated controls in-station that will detect discrepant part and notify operator (light, buzzer etc). Gauging performed on setup and first piece check (for set up causes only)
4	Moderately High	Controls have good chance to detect	X	X		Failure mode detection post-processing by automated controls that will detect discrepant part and lock part to prevent further processing.
3	High	Controls have good chance to detect	X	X		Failure mode detection in-station by automated controls that will detect discrepant part in station to prevent further processing.
2	Very High	Controls almost certain to detect	X	X		Error (cause) detection in-station by automated controls that will detect error and prevent discrepant part from being made.
1	Certain	Controls certain to detect	X			Error (cause) prevention as a result of fixture design, machine design or part design. Discrepant parts cannot be made because item has been error proffed by process/product design.

Inspection Type: A= Error Proof / B= Gauging / C= Manual Inspection

Table 15 - Detection Ranking

Finally, the RPN is calculated and uses a colour coordination matrix as per table 16 below. As well as identifying faults, the FMEA allows actions to take place which will reduce the RPN value. This should be constantly reviewed until the value is as low as reasonably practicable (ALARP).

RPN Rank	
RPN	Description
1000	Highest possible - do something immediately
512	High risk - as above
125	Moderate risk - take some action
<100	Address if all above have been mitigated

Table 16 - RPN Rank

9.4. Installation

The majority of the equipment installation for the project was completed in-house, leveraging the expertise of the internal team to manage costs and ensure efficient execution. However, certain specialised activities required outsourcing to contractors. When contractors were brought on-site, strict compliance with safety protocols were maintained. A permit-to-work system was implemented, as outlined in figure 57, supported by comprehensive risk assessments and method statements as part of the Control of Contractors policy. These measures ensured that all activities adhered to the required safety standards and minimised risks during installation.

THIS PERMIT NEEDS TO BE DISPLAYED AT ALL TIMES

WALLCOLMONEY Authorisation to Work		1. Name of Company: 2. PO Number:		3. Date Issued: 4. Permit Number: 1904	
7. Permit Req'd: Tick ✓ Confined Spaces 8. Location of work and plant identification:		Hot Work Mobile Crane Excavation Asbestos		5. Start Date & Time: 6. Finish Date & Time:	
9. Description of Work to be carried out: 10. Risk Assessment Method Statement & Liability Insurance Provided by Contractors:		14. Environmental Risks: will the task create/generate - Waste? Emissions to air? Emissions to water? Smoke/odour? Light nuisance? Noise nuisance? Other:		15. Protective Equipment: Goggles / Glasses Gloves / Gauntlets Safety Footwear Hearing Protection Hard Hat HPE / Dust Mask Safety Harness Molten Metal Clothing	
11. Any sub-contractors to be used (own ATW is req'd)		16. Services to be isolated: Eng. Name & Sign Are spill arrangements in place? Are sewers, drains, sealed within 6m		17. Hazardous substances Advise relevant departments of any intended isolation & signage posted.	
12. General Requirements: 1. Have all employees received a site induction? 2. Have all employees read and signed the risk assessment? 3. Are the workforce competent to carry out the task? 4. Are personnel aware of access/egress means of escape and method of raising alarm? 13. Hazards and Precautions to be taken: 1. Are mobile cranes or mobile plant to be used? 2. Asbestos 3. Moving machinery 4. Hot work 5. Working at height 6. Falling objects 7. Pressure systems 8. Molten metal 9. Gaseous atmosphere 10. Noise 11. Electrical 12. Traffic - internal and external 13. Lone working 14. Hazardous substances 15. Other:		Yes No N/A (Please tick)		Yes No N/A Specify	
19. Issuing Authority: WCL Engineering Name WCL Production Name		20. Contractor Company representative: Name		21. Hand Back: Contractor I certify that all work is completed and all persons under my charge have been withdrawn and told it is no longer safe to return, all permits and safety devices reinstated and the area clear. Name: Signature:	
22. Cancellation: I certify that all the work is complete, the area has been inspected and the permit is now cancelled. (WCL Representative) Name: Signature:		23. Cancellation: I certify that all the work is complete, the area has been inspected and the permit is now cancelled. (WCL Representative) Name: Signature:		24. Cancellation: I certify that all the work is complete, the area has been inspected and the permit is now cancelled. (WCL Representative) Name: Signature:	

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Figure 57 - Permit to Work Template

One of the critical tasks during installation involved positioning the air classifier. This was achieved using a forklift to ensure precise placement. The successful installation of the air classifier is depicted in figure 58 and figure 59, highlighting its integration into the overall system.



Figure 58 - Forklift Installation of Air Classifier Base



Figure 59 - Air Classifier Installed

The installation of the vibratory screener, another essential component in the process, is shown in figure 60. This equipment was installed in a manner that optimises its efficiency in classifying and separating particles within the defined particle size distribution (PSD).



Figure 60 - Vibratory Screener Installed

Downstream of the air classifier and vibratory screener, two hoppers were incorporated to manage material flow. As illustrated in figure 61, the right hopper collects particles smaller than 20 microns (<20 microns), while the left hopper feeds material into the vibratory screener via a pneumatic conveyor for further separation.



Figure 61 - Air Classifier Hopper Collection

The pneumatic conveyor, depicted in figure 62, is a key part of the material handling system. It ensures smooth and efficient transfer of materials from the hopper to the vibratory screener, minimising handling losses and ensuring consistent feed rates.



Figure 62 - Pneumatic Conveyor

To maintain a safe processing environment, an ATEX-certified extraction unit with a blast vent was installed, as shown in figure 63. This system is critical for managing dust and mitigating risks associated with potentially explosive atmospheres, ensuring compliance with industry safety standards.



Figure 63 - Extraction Unit

The overall process flow, including the integration of these components, is captured in figure 64. This figure also highlights the Programmable Logic Controller (PLC) control panel, which supports multiple sensors for real-time process control and data acquisition. This setup embodies Industry 4.0 principles, enabling advanced automation and monitoring capabilities.



Figure 64 - Overall Process

Finally, the Human-Machine Interface (HMI), shown in figure 65, provides operators with an intuitive platform for managing the system. The HMI enables easy monitoring and control of the process, ensuring quick adjustments to maintain efficiency and address any issues as they arise.



Figure 65 - HMI Interface

9.5. DMAIC Implementation

The Define phase of the project focused on addressing the inefficiencies in WCL's current screening methods, which were outdated and incapable of effectively processing fine-grade powders (<20 microns) essential for additive manufacturing technologies. These limitations created a bottleneck in production, negatively impacting throughput, quality, and yield. The primary objective of this phase was to evaluate the performance of existing screening technologies and identify an optimised solution to enhance yield, improve right-first time (RFT) results, and increase throughput. To achieve this, a systematic comparison of rotary, vibratory, and air classification screening methods was planned, setting the foundation for further analysis and improvements.

During the Measure phase, data was collected to establish baseline performance and evaluate the key factors affecting screening efficiency. Trials were conducted using a Rotex Locker for rotary screening, a TD100 for air classification, and screeners from Virto and Russell Finex for vibratory screening. The performance of each screener was measured using critical variables, including feed rate, RFT success, and yield. Yield was observed to decrease when rescreening was required, highlighting areas of inefficiency. Manual methods, including the use of a stopwatch, pen and paper, and Excel, were employed to record and analyse the data. Optimisation efforts included adjusting screener parameters to align with the specific requirements of WCL powders. Laboratory equipment, such as ROTAP and laser diffraction for particle size analysis, and a Scanning Electron Microscope (SEM) and Morphologi M4 for morphology assessments, were utilised.

The Analyse phase translated the raw data from the trials into actionable insights, focusing on identifying inefficiencies and opportunities for optimisation. Statistical tools and methodologies were applied to assess screening efficiency, yield, and throughput for each technology. The analysis revealed the impact of variables such as feed rate, particle size distribution, and screener parameters on performance. All particle size testing adhered to ASTM B214 standards, ensuring consistency and reliability, and the results were compared against WCL's defined specifications. This phase provided the necessary understanding to address inefficiencies and guided the development of an optimised screening process tailored to WCL's requirements.

The Improve phase involved implementing changes to address the inefficiencies identified during analysis. A Capital Expenditure (CapEx) project was initiated to integrate the optimised screener solution. The project included a detailed Gantt chart for scheduling, budget management plans, and coordination with contractors. Comprehensive documentation,

comprising Management of Change (MOC), Failure Mode and Effects Analysis (FMEA), Safe Work Instructions (SWI), and Standard Operating Procedures (SOPs), was developed to ensure smooth execution. The implementation followed a two-phase commissioning process, dry commissioning to confirm system functionality within the defined scope and product commissioning to validate performance under operational conditions. These efforts ensured the improvements met project objectives and stakeholder expectations.

Finally, the Control phase focused on sustaining the benefits of the implemented solution and ensuring long-term operational excellence. Post-installation, the performance of the optimised screener will be monitored regularly to verify alignment with the CapEx justification and payback targets. Routine evaluations and process audits will be conducted to track key performance indicators (KPIs), such as screening efficiency, yield, and throughput, ensuring the system continues to operate as intended. Any deviations will be addressed promptly through adjustments to maintain optimal performance. Additionally, training materials and documentation developed during implementation will support consistent operation and adherence to best practices. These control measures will ensure the improvements remain effective over time, supporting WCL's goals of enhancing productivity and meeting the demands of additive manufacturing technologies.

9.6. Summary

The successful implementation of a combined air classification and vibratory screening system requires careful planning and execution, supported by comprehensive project documentation, a structured MOC process, and a thorough FMEA. These steps are essential to ensuring that the new system operates efficiently, meets production goals, and mitigates potential risks to product quality and safety. The integration of air classification with vibratory screening will enable the production of fine powders with improved throughput, better yields, and right-first time (RFT) quality, which are critical for advanced manufacturing and medical applications. Through the application of best practices in project management and risk assessment, the combined system will provide the precision and reliability needed to meet the growing demand for fine-grade powders.

10. Benefits to Wall Colmonoy

The current use of four rotary screening systems, referred to as lockers, in the production line has served its purpose adequately for decades. However, with the increasing demand for fine-grade powders, particularly those under 20 μm , there is a compelling need to upgrade the screening technology at Wall Colmonoy. This section provides a detailed justification for replacing the existing locker systems with a new combined air classification and vibratory screening system. The proposed system offers significant advantages in terms of throughput, yield, right-first time (RFT) quality, and overall efficiency, making it a strategic investment for future production needs.

10.1. Throughput Improvements

One of the primary drivers for this upgrade is the need to increase throughput. The existing locker systems are limited in capacity to process large volumes of material efficiently. For example, the maximum throughput achieved by the lockers is around 150 kg/hr (example shown in figure 66) based on the 2023 data, which is insufficient to meet the growing production demands.

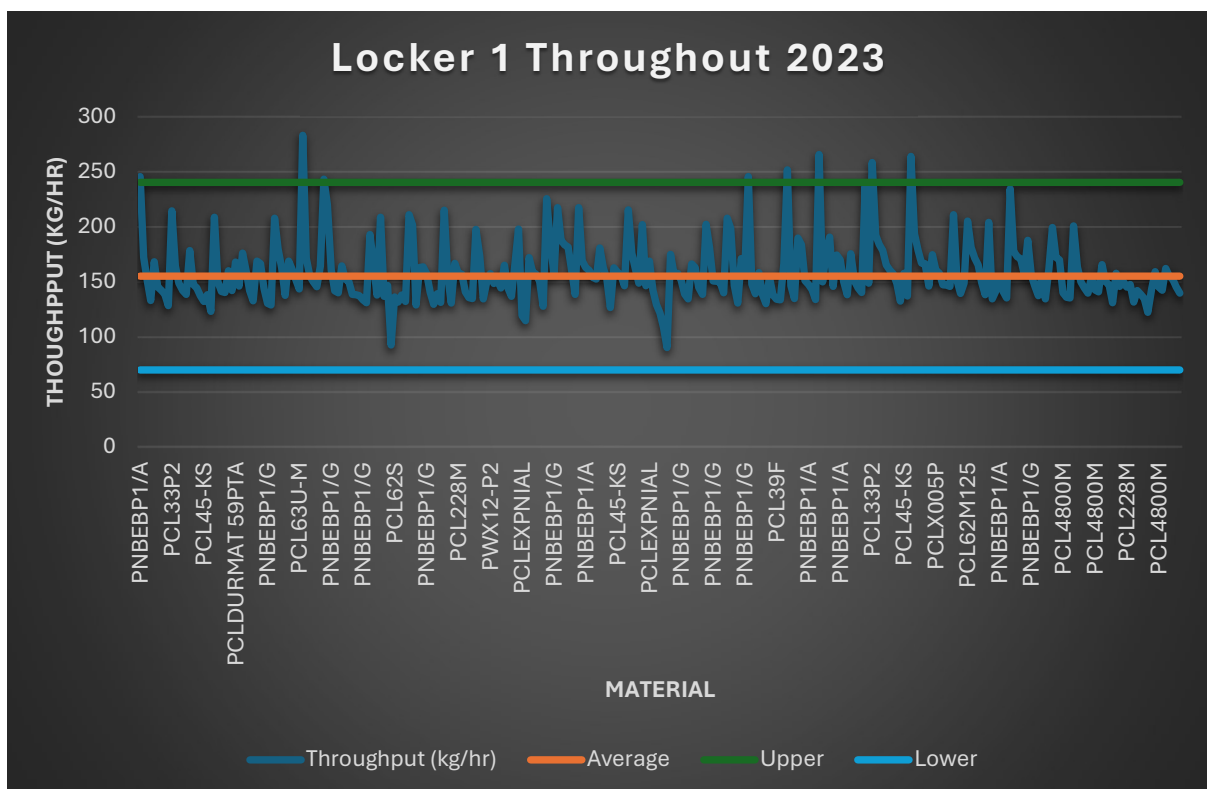


Figure 66 - KPI Graph on Throughput Rates

In contrast, the combined air classification and vibratory screening system has demonstrated the ability to handle feed rates up to 300 kg/hr, as evidenced by the Russell Finex and Air Classification trials, which is a 50% improvement. This significant increase in throughput will not only meet current production requirements, but also provide the capacity for future growth and eliminate bottlenecks in the screening process.

10.2. Right-First Time (RFT) Quality

The combined system's ability to consistently produce fine powders with the desired particle size distribution translates to improved RFT quality. The trials highlighted that the vibratory screening system could maintain a high degree of accuracy in particle separation, with minimal deviation from the target specifications. This consistency is crucial for applications in additive manufacturing (AM) and medical fields, where precision and reliability are paramount. The implementation of this new system will reduce the frequency of reprocessing and rejects, thereby enhancing overall production efficiency, reducing costs, and reduce waste. From analysis of 2023 data, the RFT screening performance was ~59%. From the trials the new screening technique achieved 80% RFT as seen in figure 67. This is a 21% improvement to RFT rates. If the project was not to happen then the company would not be able to make improvements to the bottom line and would be less competitive in the market.

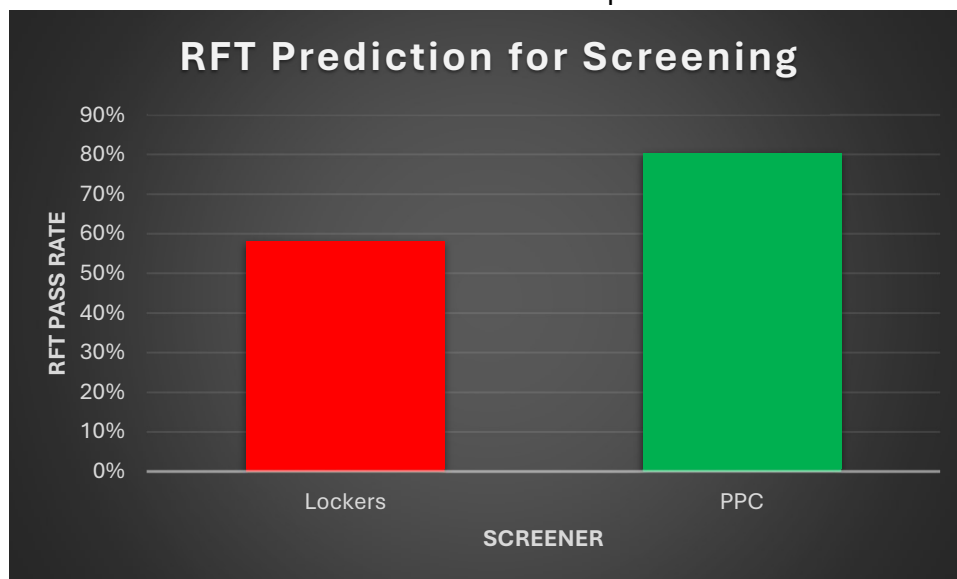


Figure 67 - RFT Prediction for Current vs New Technology

10.3. Efficiency and Cost Savings

Replacing the four locker systems with the combined air classification and vibratory screening system will result in significant operational efficiencies. The current locker systems require extensive maintenance and frequent downtime due to screen blinding and mechanical wear. The new system, with its advanced design and automation capabilities, will reduce maintenance requirements and increase operational uptime. The effect of poor efficiencies in

the process is detrimental to the business in several ways. As demonstrated in previous chapters, not having a high right first time will directly impact the yield of the product. Yield is a key driver to improving the bottom line of the organisation which aids in being competitive in the market. Similarly, waste from the production line is reliant on high yield and RFT rates as the more material being returned to inventory has the potential to significantly impact the business growth and profitability, as Nickel is a volatile element in terms of cost. There have been several events where Nickel costs have dropped, which would result in revaluating the cost of the inventory which could lead to a significant loss to the business and even wipe out annual profits of the company. To make up for lost business, it often results in having higher market value of the products compared to competitors which opens the door in the market. Thus, it is crucially important to continually monitor efficiencies of the screening equipment by use of KPI charts with regular audits of process and keeping on top of maintenance routines. These control methods will prevent complacency in the manufacturing operations.

From analysing the 2023 production data, it showed that across all five locker systems a total of 512 screen changes took place. Per change it takes roughly 32 minutes and requires 2 operators. This equates to 546 operator hours at a yearly cost of £16k. However, from trials with the new screener, the screen change over system only needs one operator for this operation and takes approximately 17 minutes per change. Therefore, the annual operator hours needed is reduced to 145, with a yearly cost of £2k. This results in an annual saving of £145k (87%), as shown in table 17.

Action	Lockers	PPC
Screen Changes	512	512
Mins per change	32	17
No. Operators	2	1
Operator Hours	546	145
Hourly rate	£ 15.00	£ 15.00
Yearly cost	£ 16,384.00	£ 2,176.00
Savings	£ 14,208.00	87%

Table 17 - Screen Changing Saving

The current lockers have a 5.5Kw motor on each screener, which across five lockers gives a consumption of 27.5kW. Across the five lockers, the throughput varies from 114kg/hr to 155kg/hr, which results in an average throughput rate of 134kg/hr. With a total run time of 5,096 hours for the 2023, and at an energy price of £0.33/kwh, this results in a yearly expenditure of £46k. Whereas, with the air classifier system, vibratory screener, and control system, this totals 10.2kw per complete screener. Based on two new complete systems and a total runtime of only 2,279 hours based on the throughput improvements to run the same

amount of material, the annual run cost reduces to ~£15k. This is a saving of ~£30k/year, netting a 67% improvement, as shown in table 18.

Action	Lockers	PPC
Throughput	134	300
kW of Uni	5.5	10.2
Number of units	5	2
Total kW	27.5	20.4
Total Hours	5096	2,279
Energy Price	£ 0.33	£ 0.33
Annual Run Cost	£ 46,243.18	£ 15,339.38

Annual Cost Saving / Year	£ 30,903.80
Improvement	67%

Table 18 - Energy Savings

Due to the yield increases proposed, the amount of raw material needed to produce 2023's capacity will reduce. Based on screening 700T at a yield of 22% this required melting 1,556 450kg batches. These furnaces run for 90 minutes per melt which needs 325kw of power during this time. Thus the electrical cost for 2023 was £250k for these melts, whereas based on the yield increase only ~496T of raw material is required which reduces the number of melts to 1,104. This reduces the annual electrical cost to £177k which has an annual saving of £72k, netting a 29% improvement, as shown in table 19.

Action	Lockers	PPC
Melt Capacity	700,000	496,774
Batch Size	450	450
Melts	1,556	1,104
Melt Time	1.5	1.5
Power	325	325
Energy Consumption	758,333	538,172
Electric Cost	£ 0.33	£ 0.33
Annual Cost	£ 250,250	£ 177,597
Savings	£ 72,653	29%

Table 19 - Melt Cost Savings

Finally, as the new screening systems also offer increased capacity, if 700T was run through the new screening route, at the increased yield, it would increase the sellable material from 154T to 217T which takes the annual revenue to £9m from £6.5m. Based on keeping the profit margin at 5% this would increase from £323k to £454k. An increase of £132k profit, equating to a 29% improvement, as described in table 20.

Action	Lockers	PPC
Annual Material (kg)	700,000	700,000
Yield	22%	31%
Sellable Material	154,000	217,000
Selling Price/Kg	£ 42.00	£ 42.00
Annual Revenue	£ 6,468,000	£ 9,114,000
Profit Margin	5%	5%
Annual Profit	£ 323,400.00	£ 455,700.00
Savings	£ 132,300.00	29%

Table 20 - Profit Increase

10.4. Return on Investment (ROI)

The financial justification for replacing the locker systems with the combined air classification and vibratory screening system is compelling, when considering the return on investment (ROI). The initial capital investment for the new system is estimated at £1.17 million for two systems. However, this cost is offset by the substantial operational savings and revenue enhancements it brings.

Firstly, the increased throughput capability translates directly into higher production volumes. With the potential to process up to 300 kg/hr compared to the 150 kg/hr of the locker systems, the new system can effectively double the output. Assuming an average product price of £42 per kilogram, this increase in throughput could generate an additional £132 thousand in annual revenue, based on the historic data. Safety systems have been considered such as interlocks and extraction systems. A traffic light system has also been considered with an alarm to indicate finish times and any problems during the run cycle.

Secondly, the improved yield and RFT quality reduce waste and reprocessing costs. The air classification system's precision ensures a higher proportion of in-specification product, decreasing the need for rework. This improvement in efficiency is estimated to save approximately £23 thousand annually in material and labour costs. Additionally, optimised energy consumption can save approximately £73 thousand per year in electricity costs, in terms of melt savings.

Overall, the combined annual savings amount is approximately £250 thousand. With an initial investment of £1.17 million, the payback period for the new system is 4.7 years, as shown in table 21.

Action	Saving	
Labour	£	14,208.00
Electricity	£	30,903.80
Profit	£	132,300.00
Melt Savings	£	72,653
Savings / year	£	250,065.09
ROI		4.7

Table 21 - Project ROI

Based on the figures outlined in table 21, over the next decade the company can expect to be in profit of over £1.25m as shown in figure 68. These figures are all monetary values and don't consider maintaining customer relationships, increasing competitive advantages, and complying to all relative standards.

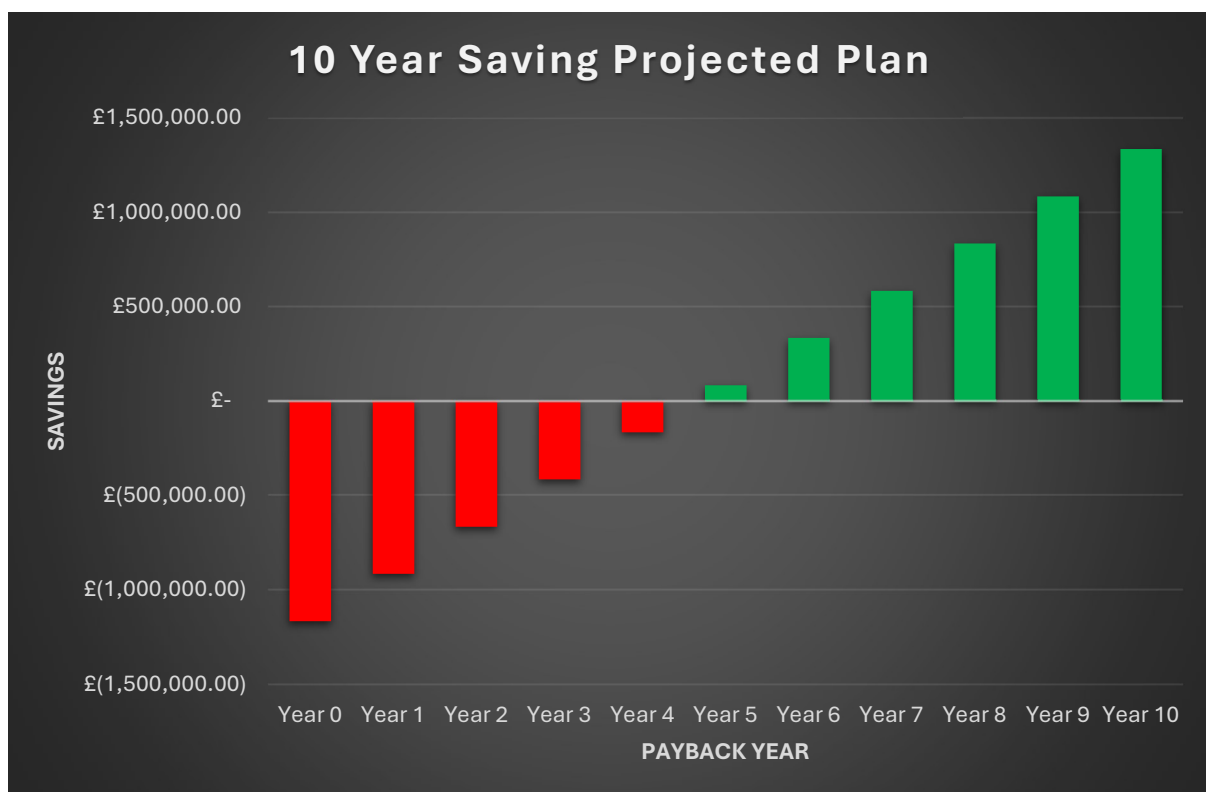


Figure 68 - Savings over 10 years

10.5. Technological Advancement and Futureproofing

Investing in the combined air classification and vibratory screening system, positions the company at the forefront of technological advancement. The system's ability to produce sub-25 µm powders with high precision aligns with the future trends in AM and medical applications, where the demand for ultra-fine powders is expected to grow. By upgrading to this state-of-the-art system, the company not only enhances its current production capabilities, but also future proofs its operation against evolving market demands and technological advancements.

10.6. Overall Equipment Effectiveness

Overall Equipment Effectiveness (OEE) is a critical metric for evaluating the performance of manufacturing equipment by integrating three core components: availability, performance, and quality. OEE is calculated as the product of these factors, expressed as a percentage, as shown in equation 4.

$$OEE = Availability (A) \times Performance (P) \times Quality (Q)$$

Equation 4 – Overall Equipment Effectiveness Equation

Availability measures the proportion of scheduled time that the equipment is operational, accounting for downtime. Performance assesses the speed at which the equipment operates relative to its designed capacity. Quality evaluates the proportion of output that meets specifications without requiring rework or rejection. By identifying losses in these three areas, OEE provides a comprehensive framework for pinpointing inefficiencies and driving continuous improvement. In the context of screening technologies, calculating OEE enables a detailed understanding of how factors like mesh blinding, feed rate variations, and particle morphology impact operational effectiveness, offering actionable insights for process optimization. Historic analysis was conducted on the locker systems on OEE. As shown in figure 69 there's no consistency with the lowest being ~8% and the highest being ~28% with an average of 17%. These figures are far too low and show the inefficiencies of the system. It

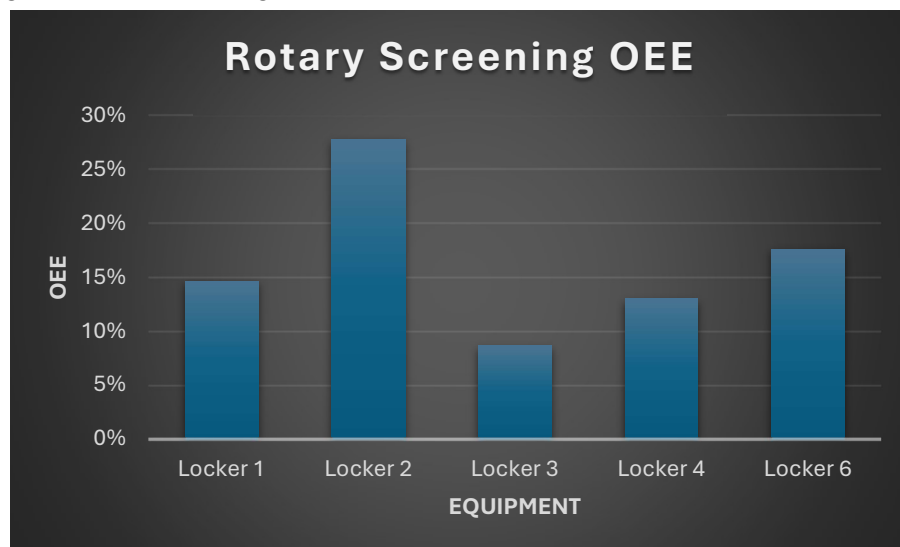


Figure 69 - OEE of Lockers

is predicted that the new screening system will have an OEE of 55%, as shown in figure 70. This is still relatively low compared to other industries, such as automotive where the OEE is up of 85% (Dobra & Josvai, 2021). However this improvement signifies a 49% improvement.

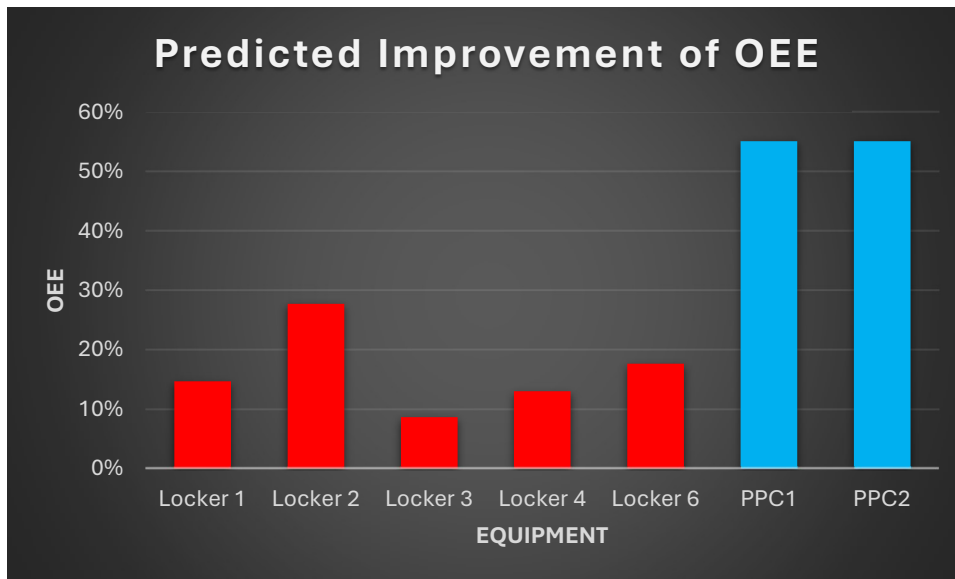


Figure 70 - OEE Improvements

10.7. Summary

The justification for replacing the existing four locker systems with a combined air classification and vibratory screening system is multifaceted and robust. The new system offers substantial improvements in throughput, yield, and RFT quality, while also providing operational efficiencies and significant cost savings. The ability to produce fine-grade powders with high precision is particularly critical for meeting the needs of advanced manufacturing and medical applications. This strategic investment will enhance production capabilities, ensure long-term competitiveness, and position the company for future growth in a rapidly evolving market. The exceptional ROI further underscores the financial viability and strategic benefit of this upgrade.

11. Quantifiable benefits

Since commissioning the new screening system, the initial results look promising. All products run through this systems are up on historic yield as shown in figure 71.

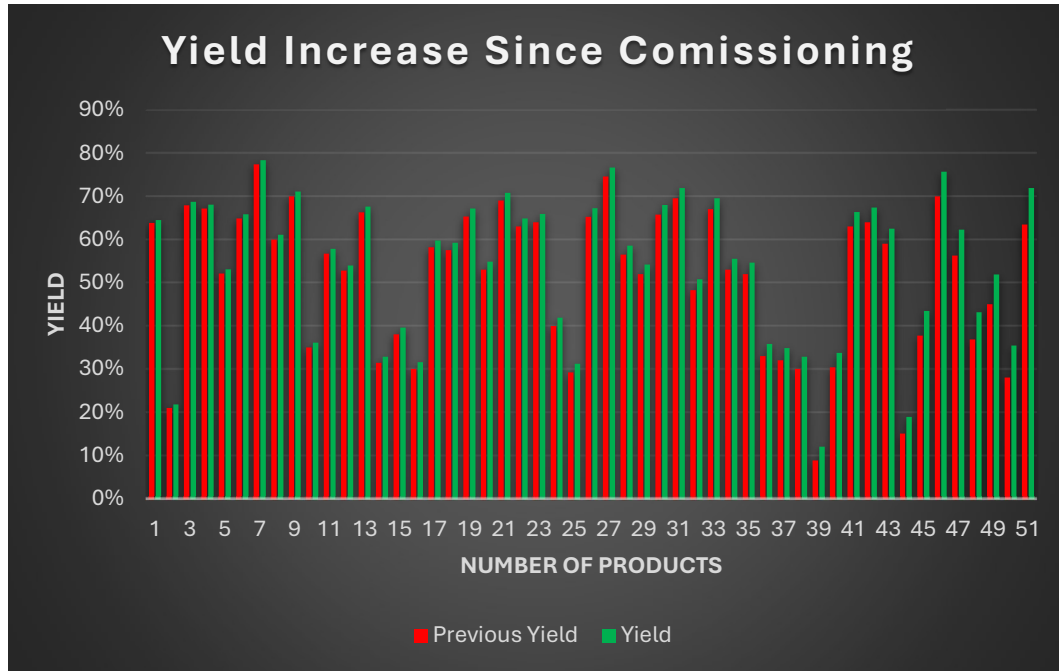


Figure 71 - Yield Increase

The throughput is also very consistent with the target with an average of 294kg/hr vs a target of 300kg/hr. The throughput is very repeatable which fits within a two sigma upper and lower limit due to the reduction in standard deviation compared to 3 sigma being used on previous data, as shown in figure 72.

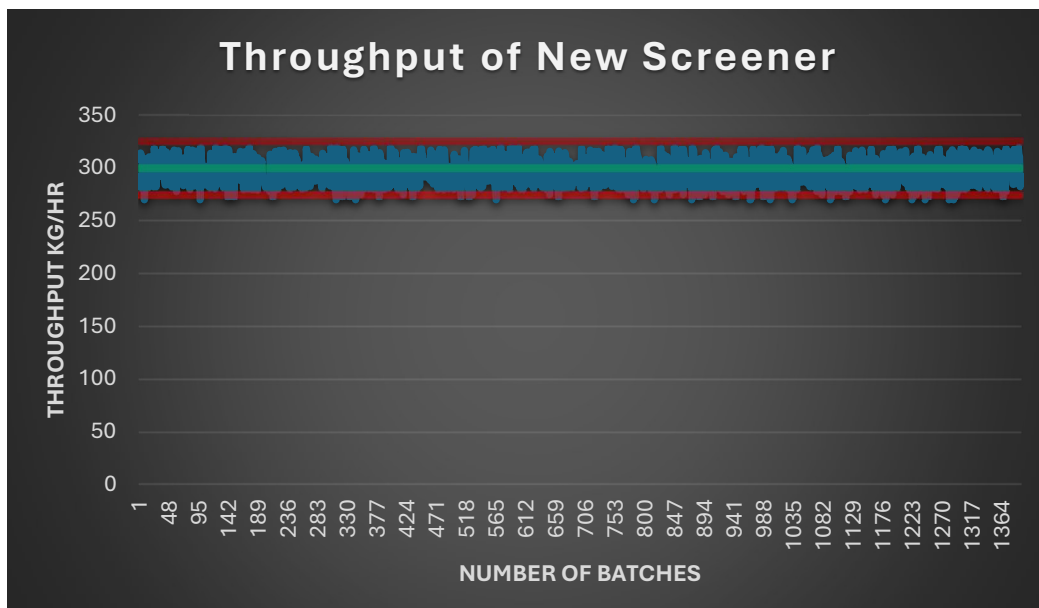


Figure 72 - Throughput consistency

Conclusion

This study has undertaken an in-depth analysis of screening technologies employed in the production of nickel and cobalt-based alloys, rigorously addressing key challenges, inherent limitations, and transformative opportunities. By conducting a comprehensive evaluation of rotary screening, vibratory screening, and air classification, this research delineates the unique advantages and constraints associated with each technology. Ultrasonic vibratory screening has demonstrated exceptional precision for the separation of ultra-fine particles, however, its scalability for large-scale industrial operations remains a limitation. Conversely, rotary screening offers high throughput for coarser powders but suffers from significant performance degradation when applied to ultra-fine materials due to mesh blinding. Air classification, with its capability to achieve aerodynamic precision and narrow particle size distributions (PSD), excels for sub-20 micron particle screening but exhibits reduced efficacy for coarser particle processing, highlighting the necessity for innovative and adaptable solutions.

This study identifies air classification as the optimal technology for sub-20 micron particles, while ultrasonic vibratory screening is most effective for +20 micron powders. Although industries traditionally adopt one approach over the other, this research underscores the synergistic benefits of hybrid systems. Implementing a combined screening system has resulted in a throughput increase from 150 kg/hr to 300 kg/hr and a Right-First Time (RFT) improvement from 58% to 81%. These gains, along with labour, electricity, yield enhancements, and reduced melt losses, deliver annual savings of £250,000. With an investment of £1.17 million for two advanced screening systems, the return on investment (ROI) is achieved in 4.7 years. Furthermore, over the next decade, the company is projected to achieve a cumulative profit increase of £1.3 million, while Overall Equipment Effectiveness (OEE) has improved significantly from 17% to 55%.

The findings of this study underscore the transformative potential of hybrid screening systems. By leveraging the complementary strengths of vibratory screening and air classification, hybrid configurations effectively address the limitations of individual methodologies. These systems enhance throughput, optimise yield, and provide unmatched PSD precision, making them especially suitable for the growing demand for ultra-fine powders in advanced applications such as additive manufacturing and thermal spraying. Such applications necessitate stringent quality standards and operational reliability, emphasizing the importance of hybrid systems in fulfilling both current and future industrial requirements. Moreover, these systems' adaptability

to diverse material properties and evolving manufacturing demands ensures their scalability and long-term viability.

Beyond technological advancements, this research highlights the critical ethical and environmental considerations inherent in nickel and cobalt production. The environmental impacts including deforestation, biodiversity loss, water contamination, and significant carbon emissions, demand a swift transition to sustainable practices. These challenges are further compounded by social issues such as labour exploitation, unsafe working conditions, and community displacement. This study advocates for a paradigm shift in production methodologies, calling for the integration of advanced screening technologies with responsible resource management. Implementing eco-friendly mining techniques, adhering to stringent labour standards, and promoting transparent sourcing policies are essential for fostering sustainable and ethically responsible production frameworks. Such measures not only mitigate environmental degradation but also align with international sustainability objectives and ethical standards.

The broader implications of this research extend to the strategic incorporation of sustainability principles within industrial practices. By optimising screening processes through hybrid systems, manufacturers can significantly reduce waste, minimise energy consumption, and enhance overall productivity. Simultaneously, embedding sustainability principles into these processes ensures compliance with regulatory frameworks and societal expectations. Hybrid approaches, which combine the precision of vibratory screening with the efficiency of air classification, deliver dual benefits: improved operational performance and a reduced environmental footprint. These advancements position manufacturers to maintain competitive advantages while contributing to the global shift toward greener industrial practices.

In conclusion, this research represents a significant contribution to the field of alloy production by addressing critical gaps in screening technologies while integrating principles of sustainability and social responsibility. By optimising screening processes and adopting hybrid solutions, manufacturers can achieve significant improvements in efficiency, precision, and scalability. These innovations enable the industry to meet the rising global demand for high-performance materials while advancing environmentally and socially conscious production practices. The insights presented in this study provide a strategic framework for the future of alloy production, guiding the industry towards a more sustainable, efficient, and equitable paradigm. This holistic approach ensures that the production of nickel and cobalt-based alloys remains aligned with broader societal, environmental, and industrial objectives, securing its relevance and viability in an increasingly resource-conscious world.

Recommendations

To advance the findings and ensure sustained progress in the optimisation of screening technologies and powder processing operations, several key strategic initiatives are proposed. While theoretical models have provided substantial insights, it is imperative to complement these with robust empirical data collection. Such data will offer a precise evaluation of actual performance improvements, validating the efficacy of implemented changes. This comprehensive analysis will not only align operational outcomes with strategic objectives but will also establish a foundation for benchmarking and future decision-making processes.

The continuation of the installation process into its second phase, involving the integration of an additional powder processing cell, is a critical next step. This phase must incorporate lessons learned during the initial installation to address and resolve prior challenges effectively. Leveraging these insights will enable the new processing cell to achieve enhanced efficiency, reliability, and scalability, ensuring alignment with long term operational and strategic goals. By systematically applying these improvements, the organisation can streamline workflows and enhance overall productivity.

Adopting a "goldfish mentality," characterised by a dynamic and iterative approach to process improvement, is essential for fostering continuous innovation. This mindset encourages all stakeholders to rigorously evaluate existing systems for latent inefficiencies and opportunities for enhancement. Regular system reviews and iterative refinements will ensure that the operational framework remains adaptable to emerging challenges and responsive to evolving production needs, thereby embedding a culture of excellence and innovation.

To further refine operations, the implementation of advanced automation and data acquisition systems is strongly recommended. These technologies should be designed to integrate seamlessly with live dashboards that provide real time visualisation of key performance indicators (KPIs). Such systems would enable the early detection of failures and deviations within the process, minimising the occurrence of defects and waste. Moreover, the transition to automation and data driven analytics will enhance decision making precision, facilitate rapid response to anomalies, and ensure that quality assurance protocols are consistently upheld across production cycles.

By undertaking these targeted initiatives, the organisation can reinforce its commitment to technological advancement, operational excellence, and sustainable manufacturing practices. These strategic actions will position the organisation to achieve both immediate and long-term objectives, ensuring a competitive advantage in an increasingly dynamic industrial landscape.

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Appendix

Appendix A – Virto Trial A PSD

Feed Rate (kg/h)	180µm	150µm	125µm	106µm	90µm	75µm	63µm	53µm	45µm	38µm	20µm	-20µm	TOTAL
15	5.2 %	3.8 %	4.1 %	5.7 %	6.4 %	7.6 %	10.3 %	9.2 %	8.5 %	9.1 %	24.3 %	5.8 %	100.0 %
22	4.9 %	3.6 %	3.9 %	5.5 %	6.3 %	7.6 %	10.8 %	9.2 %	8.6 %	9.0 %	26.7 %	3.8 %	99.9 %
30	5.1 %	3.7 %	4.2 %	5.5 %	6.6 %	7.6 %	10.4 %	9.1 %	8.8 %	8.9 %	23.8 %	6.1 %	99.8 %
60	4.7 %	3.5 %	3.9 %	5.4 %	6.3 %	7.4 %	10.4 %	9.0 %	8.5 %	9.0 %	25.3 %	6.5 %	99.9 %
90	4.9 %	3.6 %	4.0 %	5.6 %	6.4 %	7.6 %	10.5 %	9.0 %	8.5 %	8.8 %	25.2 %	6.0 %	100.1 %
120	5.1 %	3.6 %	4.0 %	5.6 %	6.4 %	7.7 %	10.4 %	9.0 %	8.5 %	9.0 %	25.0 %	5.8 %	100.1 %
Standard Deviation	0.2 %	0.1 %	0.1 %	0.1 %	0.1 %	0.1 %	0.2%	0.1 %	0.1 %	0.1 %	0.9%	0.9 %	

Table 22 - PSD Results from Virto Trial A

Appendix B – Full FMEA

 PROCESS FAILURE MODE and EFFECTS ANALYSIS											
WALLCOLMONOY											
PPC Process											
Rev No											
1											
Date											
Seq	Process step / Function	Potential Failure Mode	Potential Effects of Failure	Severity	Potential Causes / Mechanisms of Failure	Current Process Controls (Preventive)	Occur	Current Process Controls (Detection)	Defect	R.P.N.	Recommended Actions
1	Put hopper bin on stand and open sanders valve	Powder wont flow	Powder can't be processed	4	Saunders valve handle broken	None	5	Operator dependant & spares on hand	1	20	No action required
				3	Hopper not on stand correctly	None	2	Alignment rails	1	6	No action required
				7	Powder is bridged in bin	None	6	Vibration device on hopper	2	84	No action required
				7	Wet powder	Dry for 2 hours	6	None	3	126	Moisture test
2	Russel finex operation interlock	Russel decks fall off when started up	Powder can't be processed	7	Clamps not fitted correctly	None	2	Screen change device	1	14	No action required
			Damage Russell deck	7	Clamps not fitted correctly	None	2	Screen change device	1	14	No action required
			Potential injury to people	7	Clamps not fitted correctly	None	2	Screen change device	1	14	No action required
3	Load recipe	Recipe not in system	Powder can't be processed	4	New product	None	2	Supervisor dependant	4	32	No action required
				4	Not run on the equipment previously	None	2	Supervisor dependant	4	32	No action required
				6	Paperwork not with bin	Paperwork to fallow bin through process	1	Operator dependant	1	6	No action required
4	Input weight	weight unknown	Powder can't be processed	6	Paperwork not with bin	Paperwork to fallow bin through process	1	Scales in area	1	6	No action required
				4	Weight not on paperwork	Paperwork to fallow bin through process	1	Scales in area	1	4	No action required
5	Input final batch number	Final batch number unknown	Powder can't be processed	6	Paperwork not with bin	Paperwork to fallow bin through process	1	Operator dependant	1	6	No action required
				4	Final batch number not generated	Operator to generate batch no	2	Operator dependant	1	8	No action required
6	Input batch number	Batch number unknown	Powder can't be processed	2	Paperwork not with bin	Paperwork to fallow bin through process	2	Operator dependant	1	4	No action required
7	Input Screen used	Screen size unknown	Powder can't be processed	3	Not written on production board	Operator to write screen used on board	2	None	2	12	No action required
8	Process choice	Incorrect process chosen	Powder can't be processed fully	4	selected incorrect process flow	None	1	Operator dependant	1	4	No action required
9	Powder transfer to Volkmann (VP1)	No powder transfer	Powder can't be processed	6	Powder blocked in transfer pipe	None	6	Alarm System	1	36	No action required
				6	Sanders valve not open	HMI Prompted to open on start-up	1	Alarm System	1	6	No action required
				6	No compressed air	None	1	Pressure transducers & alarm system	1	6	No action required
				6	Powder blocked in AA hopper	None	6	Traffic light system to indicate powder flow	1	36	No action required

				6	Automated valve (AV1) not working	None	2	Alarm System	2	24	No action required
				5	Vacuum of Volkmann(VP1) low	Maintenance checks every month	2	Alarm System	2	20	No action required
				5	HMI not working correctly	None	1	None	1	5	No action required
				5	Solenoid (S1) not working	None	1	Alarm System	1	5	No action required
				5	Low pressure on plant compressed air	None	1	Pressure transducers & alarm system	2	10	No action required
				5	Plant compressed air wet	Set of filters in place	1	Preventative Maintenance	2	10	No action required
				5	Digital pressure (DP1) not working	None	1	Alarm System & HMI Feedback	2	10	No action required
				5	Incorrect setting on pressure gauge	None	1	Alarm System	2	10	No action required
				6	Hole in transfer pipe	Maintenance checks every month	5	Alarm System	2	60	No action required
				5	Transfer pipe is not connected	None	3	Alarm System	1	15	No action required
				6	Incorrect recipe set point	None	2	None	2	24	No action required
				6	Incorrect Automated valve (AV1 set point	None	2	None	2	24	No action required
				6	Transfer pipe elongated	None	6	Alarm System	2	72	Review - combination of S and O
				6	No powder in bin	None	5	Traffic light system to show no powder flow	1	30	Review - combination of S and O
				7	Wet powder	None	6	Alarm System	1	42	Review - combination of S and O
				4	Incorrect process route selected	None	2	No Powder transfer to Volkmann	2	16	No action required
		Low or no pressure on digital gauge	Powder can't be processed	5	Powder in the pipe from Volkmann pump and digital pressure gauge	None	3	Visual display on HMI and digital gauge	2	30	No action required
		Low vacuum pressure on Volkmann (VP1)	Powder can't be processed	5	Incorrect Automated valve (AV1 set point	None	2	Visual - Set point on main HMI screen	2	20	No action required
				5	Low pressure on plant compressed air	None	1	Alarm System	1	5	No action required
				5	Plant compressed air wet	In line filter	1	Preventative Maintenance	2	10	No action required
				5	Digital pressure (DP1) not working	None	1	Visual display on HMI screen and No powder flow	1	5	No action required
				5	Incorrect setting on pressure regulator gauge	None	1	Visual display on HMI screen and No powder flow	2	10	No action required
				6	Hole in transfer pipe	Maintenance checks every month	6	Pressure transducers & alarm system	2	72	Review - combination of S and O
				5	Transfer pipe is not connected	None	3	Alarm System	1	15	No action required
				6	Volkmann Discharge flap not closed	Maintenance checks every month	4	Pressure transducers & alarm system	2	48	Review - combination of S and O
				6	No compressed air	None	1	Pressure transducers & alarm system	1	6	No action required
10	Powder discharge to buffer hopper (BH1)	Powder wont transfer to buffer hopper (BH1)	Powder can't be processed	6	No compressed air	None	1	Pressure transducers & alarm system	1	6	No action required
				5	Solenoid (S2) not working	None	1	Weight shown on praction controller	1	5	No action required

				5	Solenoid (S2) pipe not connected	None	1	Weight shown on praction controller	1	5	No action required
				5	Solenoid (S2) regulator too low	None	1	Weight shown on praction controller	1	5	No action required
				4	Incorrect process route selected	None	2	Pressure transducers & alarm system	2	16	No action required
				6	Incorrect set point in recipe	None	2	Pressure transducers & alarm system	2	24	No action required
11	Powder transfer to vibratory feeder (VF1)	Powder wont transfer to vibratory feeder (VF1)	Powder can't be processed	6	Powder buffer hopper (BH1) blocked at outlet	None	5	Low feed rate indicated on HMI screen	2	60	Review - combination of S and O
				7	Transfer sleeve split	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				3	No cable tie connected to vibratory feeder (VF1)	None	2	Feed rate indicated on HMI screen	2	12	No action required
				3	Sleeve not attached to buffer hopper 1 (BH1)	None	2	Feed rate indicated on HMI screen	2	12	No action required
		Transfer sleeve failure	Powder can't be processed	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
			Fugitive dust	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
			Damage to Vibratory feeder (VF1)	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
12	Vibratory feeder (VF1)	No material flowing	Powder can't be processed	6	Feeder Motor not working correctly	Maintenance checks every month	5	Feed rate indicated on HMI screen	2	60	Review - combination of S and O
				6	Incorrect set point on (FRC1)	None	2	Feed rate indicated on HMI screen	3	36	No action required
				6	Incorrect set point in recipe	None	2	None	3	36	No action required
				7	VF1 Transfer pipe blocked	None	4	Low feed rate and traffic light stem to show no powder flow	1	28	Review - combination of S and O
				6	Incorrect process route selected	None	2	Alarm System	2	24	No action required
		Material transferring slow	Powder processed incorrectly	6	Feeder Motor not working correctly	Maintenance checks every month	5	Alarm System	2	60	Review - combination of S and O
				6	Incorrect set point on (FRC1)	None	2	Feed rate indicated on HMI screen	2	24	No action required
				6	Incorrect set point in recipe	None	2	None	3	36	No action required
				7	VF1 Transfer pipe blocked	None	4	Low feed rate and traffic light stem to show no powder flow	2	56	Review - combination of S and O
		Material transferring fast	Powder processed incorrectly	6	Feeder Motor not working correctly	Maintenance checks every month	2	Feed rate indicated on HMI screen	2	24	No action required
				6	Incorrect set point on (FRC1)	None	2	Feed rate indicated on HMI screen	2	24	No action required
				6	Incorrect set point in recipe	None	2	None	3	36	No action required

13	Classifier (CL)	Classifier rotor not tuning	Powder can't be processed	4	Motor isolator has tripped in HMI (M3)	None	4	Red light on HMI panel	1	16	No action required
				5	Motor is not working	None	3	None	3	45	No action required
				5	Motor belt has broken	None	5	None	3	75	Review - combination of S and O
				5	Bearing damaged	None	2	None	3	30	No action required
				5	Incorrect process route selected	None	2	Alarm System	1	10	No action required
		Classifier rotor tuning slow	Powder processed incorrectly	5	Motor belt is loose	None	3	Preventative Maintenance	3	45	No action required
				5	Motor performance	None	3	Preventative Maintenance	3	45	No action required
				5	Bearing damaged	None	3	Preventative Maintenance	3	45	No action required
				6	Incorrect set point in recipe	None	3	Preventative Maintenance	3	54	No action required
				6	Incorrect recipe selected	None	3	Preventative Maintenance	1	18	No action required
14	Rotary valve 1(RV1)	Air seal pressure not correct	Fugitive dust	5	Incorrect regulator set point (PG1)	None	2	Powder discharge from shaft & Alarm system	2	20	No action required
				5	Compressed air not connected	None	2	Powder discharge from shaft & Alarm system	2	20	No action required
				5	Solenoid faulty (S3)	None	2	Powder discharge from shaft & Alarm system	2	20	No action required
				5	No plant compressed air	None	2	No Powder transfer to Buffer hopper & pressure transducer & alarm system	1	10	No action required
				6	shaft worn	None	3	Powder discharge from shaft	2	36	No action required
		Not turning	Powder can't be processed	6	Motor (M4) not working	None	2	None	2	24	No action required
				5	Motor (M4) tripped	None	2	Red light on HMI panel	1	10	No action required
				6	Drive Belt damaged	None	2	None	2	24	No action required
				5	Incorrect regulator set point (PG2)	None	2	Alarm System	2	20	No action required
				5	Compressed air not connected	None	2	Alarm system	2	20	No action required
15	Rotary valve 2(RV2)	Air seal pressure not correct	Fugitive dust	5	Solenoid faulty (S4)	None	2	Alarm system	2	20	No action required
				5	No plant compressed air	None	2	Pressure transducers & alarm system	1	10	No action required
				6	shaft worn	None	3	Alarm System	2	36	No action required
		Not turning	Powder can't be processed	6	Motor (M5) not working	None	2	None	2	24	No action required
				5	Motor (M5) tripped	None	2	Red light on HMI panel	1	10	No action required
				6	Drive Belt damaged	None	2	None	3	36	No action required
16	Fines bin	Leaking material	Fugitive dust	6	Extraction not working	None	3	Red light on HMI panel	1	18	No action required
				6	Hopper valve not closed	None	4	Operator dependant	2	48	Review - combination of S and O
				6	Extraction pipe not connected	None	6	Operator dependant	2	72	Review - combination of S and O
				6	Extraction pipe damaged	None	2	Operator dependant	2	24	No action required
				6	Transfer pipe damage	None	2	Operator dependant	2	24	No action required
				6	Lids damaged	None	2	Operator dependant	2	24	No action required
17	Product and oversize bin	Leaking material	Fugitive dust	6	Hopper too full	None	1	Operator dependant	2	12	No action required
				6	Extraction not working	None	6	Operator dependant	2	72	Review - combination of S and O
				6	Extraction pipe not connected	None	2	Operator dependant	2	24	No action required
				6	Extraction pipe damaged	None	2	Operator dependant	2	24	No action required
				6	Transfer pipe damage	None	2	Operator dependant	1	12	No action required
		Material not	Powder can't be processed	4	Butterfly valve closed	None	3	Alarm System	1	12	No action required

		transferring to tundish		4	Too much vacuum pressure	None	3	Alarm System	1	12	No action required
18	Product and oversize scale (FS1)	Incorrect weight too light	Powder can't be processed	5	Faulty load cell	None	2	Feedback to PLC	1	10	No action required
				5	Zero or teared scale	None	2	Feedback to PLC	2	20	No action required
			No Signal to HMI for Volkmann 2 (VP2) to start	5	Faulty load cell	None	2	Feedback to PLC	2	20	No action required
				5	Zero or teared scale	None	2	Feedback to PLC	1	10	No action required
				5	Set point not reached	None	3	Feedback to PLC	1	15	No action required
				5	Time set point not reached	None	1	Feedback to PLC	2	10	No action required
19	Powder transfer to Volkmann (VP2)	No powder transfer	Powder can't be processed	6	Powder blocked in transfer pipe	None	6	Alarm System	1	36	Review - combination of S and O
				4	Butterfly valve not open	None	3	Alarm System	1	12	No action required
				6	No compressed air	None	1	Alarm System & HMI Feedback	1	6	No action required
				6	Powder blocked in hopper	None	6	Traffic light system to indicate powder flow	1	36	Review - combination of S and O
				6	Automated valve (AV2) not working	None	2	Alarm System	2	24	No action required
				5	Vacuum of Volkmann(VP2) low	Maintenance checks every month	2	Alarm System	2	20	No action required
				5	HMI not working correctly	None	1	Alarm System	1	5	No action required
				5	Solenoid (S5) not working	None	1	Alarm System	1	5	No action required
				5	Low pressure on plant compressed air	None	1	Alarm System	2	10	No action required
				5	Plant compressed air wet	Set of filters in place	1	None	2	10	No action required
				5	Digital pressure (DP2) not working	None	1	Alarm System	2	10	No action required
				5	Incorrect setting on pressure gauge	None	1	Alarm System	2	10	No action required
				6	Hole in transfer pipe	Maintenance checks every month	5	Alarm System	2	60	Review - combination of S and O
				5	Transfer pipe is not connected	None	3	Alarm System	1	15	No action required
				6	Incorrect recipe set point	None	2	None	2	24	No action required
				6	Incorrect Automated valve (AV2 set point)	None	2	None	2	24	No action required
				6	Transfer pipe elongated	None	6	Alarm System	2	72	Review - combination of S and O
				6	No powder in bin	None	5	Traffic light system to show no powder flow	1	30	Review - combination of S and O
				7	Wet powder	None	6	Alarm System	1	42	Review - combination of S and O
				4	Incorrect process route selected	None	2	Alarm System	2	16	No action required
		Low or no pressure on digital gauge	Powder can't be processed	5	Powder in the pipe from Volkmann pump and digital pressure gauge	None	3	Visual display on HMI and digital gauge	2	30	No action required
		Low vacuum pressure on Volkmann (VP2)	Powder can't be processed	5	Incorrect Automated valve (AV2) set point	None	2	Visual - Set point on main HMI screen	2	20	No action required
				5	Low pressure on plant compressed air	None	1	Alarm System	1	5	No action required
				5	Plant compressed air wet	In line filter	1	None	2	10	No action required
				5	Digital pressure (DP2) not working	None	1	Visual display on HMI screen and No powder flow	1	5	No action required
				5	Incorrect setting on pressure regulator gauge	None	1	Visual display on HMI screen and No powder flow	2	10	No action required

				6	Hole in transfer pipe	Maintenance checks every month	5	Pressure transducers & alarm system	2	60	Review - combination of S and O
				5	Transfer pipe is not connected	None	3	No Powder transfer to Volkmann	1	15	No action required
				6	Volkmann Discharge flap not closed	Maintenance checks every month	4	Pressure transducers & alarm system	2	48	Review - combination of S and O
				6	No compressed air	None	1	Pressure transducers & alarm system	1	6	No action required
20	Powder discharge to buffer hopper (BH2)	Powder wont transfer to buffer hopper (BH2)	Powder can't be processed	6	No compressed air	None	1	Pressure transducers & alarm system	1	6	No action required
				5	Solenoid (S6) not working	None	1	Weight shown on praction controller	1	5	No action required
				5	Solenoid (S6) pipe not connected	None	1	Weight shown on praction controller	1	5	No action required
				5	Solenoid (S6) regulator too low	None	1	Weight shown on praction controller	1	5	No action required
				4	Incorrect process route selected	None	2	No Powder transfer to Buffer hopper	2	16	No action required
				6	Incorrect septet in recipe	None	2	Weight shown on praction controller	2	24	No action required
21	Powder transfer to vibratory feeder (VF2)	Powder wont transfer to vibratory feeder (VF2)	Powder can't be processed	6	Powder buffer hopper (BH2) blocked at outlet	None	5	Low feed rate indicated on HMI screen	2	60	Review - combination of S and O
				7	Transfer sleeve split	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				3	No cable tie connected to vibratory feeder (VF2)	None	2	Feed rate indicated on HMI screen	2	12	No action required
				3	Sleeve not attached to buffer hopper 1 (BH2)	None	2	Feed rate indicated on HMI screen	2	12	No action required
		Transfer sleeve failure	Powder can't be processed	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
			Fugitive dust	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
			Damage to Vibratory feeder (VF2)	7	Powder too hot for glue 100c	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
				7	Failure in butt joint	None	7	Feed rate indicated on HMI screen	2	98	Review - combination of S and O
21	Vibratory feeder (VF2)	No material flowing	Powder can't be processed	6	Feeder Motor not working correctly	Maintenance checks every month	5	Feed rate indicated on HMI screen	2	60	Review - combination of S and O
				6	Incorrect set point on (FRC2)	None	2	Feed rate indicated on HMI screen	3	36	No action required
				6	Incorrect set point in recipe	None	2	None	3	36	No action required
				7	VF2 Transfer pipe blocked	None	4	Low feed rate and traffic light stem to show no powder flow	1	28	Review - combination of S and O

		Material transferring slow	Powder processed incorrectly	6	Incorrect process route selected	None	2	No powder transferred to Volkmann	2	24	No action required
				6	Feeder Motor not working correctly	Maintenance checks every month	5	Feed rate indicated on HMI screen	2	60	Review - combination of S and O
				6	Incorrect set point on (FRC2)	None	2	Feed rate indicated on HMI screen	2	24	No action required
				6	Incorrect set point in recipe	None	2	None	3	36	No action required
				7	VF1 Transfer pipe blocked	None	4	Low feed rate and traffic light stem to show no powder flow	2	56	Review - combination of S and O
		Material transferring fast	Powder processed incorrectly	6	Feeder Motor not working correctly	Maintenance checks every month	2	Feed rate indicated on HMI screen	2	24	No action required
				6	Incorrect set point on (FRC2)	None	2	Feed rate indicated on HMI screen	2	24	No action required
				6	Incorrect set point in recipe	None	2	None	3	36	No action required
				6	Incorrect set point in recipe	None	2	None	3	36	No action required
22	Russel finex	Low production yield	Not enough material for order	6	Incorrect screen used	None	4	Operator / supervisor dependant	2	48	Review - combination of S and O
				6	Screen plugged	None	4	Operator / supervisor dependant	2	48	Review - combination of S and O
				6	Atomised material incorrect	None	4	AA particle size analysis	2	48	Review - combination of S and O
				6	Lead angel incorrect	None	2	None	3	36	No action required
				6	Amplitude incorrect	None	2	None	3	36	No action required
				6	Motor faulty	None	2	None	4	48	No action required
		High production yield	Material not in specification	6	Incorrect screen used	None	4	Operator / supervisor dependant	1	24	Review - combination of S and O
				6	Atomised material incorrect	None	2	AA particle size analysis	1	12	No action required
				6	Motor faulty	None	2	None	2	24	No action required
23	Oversize hopper	Leaking material	Fugitive dust	6	Oversize hopper too full	None	3	Operator dependant	1	18	No action required
				6	Extraction not working	None	3	Red light on HMI panel	1	18	No action required
				6	Hopper valve not closed	None	4	Operator dependant	2	48	Review - combination of S and O
				6	Extraction pipe not connected to Russell finex	None	6	Operator dependant	2	72	Review - combination of S and O
				6	Extraction pipe damaged	None	2	Operator dependant	2	24	No action required
				6	Transfer pipe damage	None	2	Operator dependant	2	24	No action required
				6	Lids damaged	None	2	Operator dependant	2	24	No action required
21	Product hopper	Leaking material	Fugitive dust	6	Product hopper too full	None	3	Operator dependant	1	18	No action required
				6	Extraction not working	None	3	Red light on HMI panel	1	18	No action required
				6	Hopper valve not closed	None	4	Operator dependant	2	48	Review - combination of S and O
				6	Extraction pipe not connected to Russell finex	None	6	Operator dependant	2	72	Review - combination of S and O
				6	Extraction pipe damaged	None	2	Operator dependant	2	24	No action required
				6	Transfer pipe damage	None	2	Operator dependant	2	24	No action required
				6	Lids damaged	None	2	Operator dependant	2	24	No action required
22	Product scale (FS2)	Incorrect weight too light	Incorrect quantity of material	3	Faulty load cell	None	2	None	3	18	No action required
				3	Zero or tared scale	None	2	Visible on HMI screen and scales screen	2	12	No action required
				3	Bin not correctly on scales	None	2	None	2	12	No action required

				3	Powder under scales	None	2	None	3	18	No action required
		Incorrect weight too heavy	Incorrect quantity of material	3	Not tared scale at start	None	2	Visible on HMI screen and scales screen	2	12	No action required

Table 23 - Full FMEA for Installing New System

Appendix C – Full MOC

HS-015-00 Management of Change Assessment

Implementation of New Screening System			
Project Number	Project Description		Reason for Change (technical basis)
CP1242	Install hybrid screening system to include a vibratory screener and air classifier		Improvements to company bottom line and reducing waste
Department			
Alloy Products			
Requested by	Agreed by Operations that the change is required (General Manager to sign)		
Gavin John			
MOC Coordinator			
Gavin John			
Approvals Required (EHS to give final sign off)	Tic k	Signatures (signing indicates that each topic has been adequately considered and that the actions identified are suitable, sufficient and completed)	
MOC Coordinator	✓	Gavin John	
Engineering	✓	Andrew Powell	
Maintenance	✓	James Davies	
Technical	✓	Lewis Morgan	
Operations	✓	Dean Martin	
EH&S (final approval and doc. review)	✓	Chris Thomas	

Change Record					
Topic	O K (Y/N)	If not OK, list action, responsibility and completion date	Change Tracking		
			Considerations	Actions	Resp.
1 Site evaluation	N	- explosion/fire	Blast screen around extraction unit	GJ	Y
	Y	- noise	In an area where hearing protection is mandatory	N/A	
	Y	- utilities available	Sufficient auxiliaries in area		
	N	- ground stability - foundation	Structural assessment, drawings, and calculations	GJ	Y
	Y	- drainage	Not required		N/A

	N	- neighbouring activities	Production areas to be reviewed	GJ	Y
	Y	- mobile crane and FLT accessibility	Not required	N/A	
	Y	- site traffic control	Not required		
	Y	- third party risks	Not required		
	Y	- hazard quantifications	Not required		
	Y	- soil contamination	Not required		
2 Equipment selection specifications	N	- pre-purchase analysis	Screening technology to be trailed	GJ	Y
	N	- meeting design criteria and purchase order specifications	Factory acceptance testing to be held with supplier	GJ	Y
3 Material selection specifications	Y	- compatibility with product use		N/A	
	Y	- meeting/exceeding wall thickness and/or desired pressure			
	Y	- cleaned when required			
	Y	- electrical motors, panels, components and wiring conform to standards			
	Y	- fitness for intended purpose			
4 Codes	Y	- do equipment and/or processes comply with applicable codes	Stainless steel complying to BS EN10088	N/A	
	Y	- pressure vessel and piping codes			
	Y	- fire protection			
	Y	- electrical	IP10 minimum		
	Y	- noise	Comply with WCL code of conduct for noise tolerances.		
	N	- emissions (air, water)	Extraction unit to be used for any open areas	GJ	Y
5 Oxygen cleaning procedures	Y	- oxygen cleaning	Not required	N/A	
	Y	- scrapped equipment to be cleaned	Not required		

6 Welding/testing procedures	Y	- special welding requirement with regard to materials, procedures or operating conditions	To be specified and implemented by supplier		N/A	
	Y	- welding certificate	Competent manufacturers		N/A	
	Y	- radiographic inspection requirement				
	Y	- brazing material, cryogenic/no n cryogenic				
	Y	- welders qualifications				
7 Pressure testing procedures	Y	- approval test procedures available	Not a pressure system		N/A	
	Y	- hydraulic testing required				
	Y	- pneumatic testing				
	Y	- recording of testing done				
	Y	- pre-tested piping used - certificates yes/no				
	Y	- safety distances				
	Y	- certification by official bodies				
8 Overpressure protection	N	- relief valves / bursting disc required due to pressure - temperature	Only needed for ATEX rating		GJ	Y
	Y	- relief valve in cryogenic piping between isolation points	Not a pressure system		N/A	
	Y	- relief devices on liquefied gas lines				
	Y	- over-protection pressure gauges				
	Y	- pressure protection vacuum system				
	Y	- under pressure protection system				
	Y	- are pressure protection relief's and bursting discs suitably sized				

		+ safety routed/vented		
9 High/low temperature protection	Y	- safeguard personnel from hot/cold surfaces	Temperature not a factor	N/A
	Y	- alarms provided for high/low temperature in process		
	Y	- low temperature embrittlement of materials possible		
	Y	- materials protected against high temperature		
10 Electrical system	N	- electrical system conforms to regulations	To be included in the control system	N/A
	N	- grounding protection		
	N	- identification voltage		
	N	- main shut-off switch		
	N	- lock/out capability		
	N	- emergency switch		
	Y	- remote start/stop switches	Not required	N/A
	N	- electrical isolation considered	To be included in the control system	GJ Y
	Y	- back-up system	Not required	N/A
	N	- overload protection electrical equipment	To be included in the control system	GJ Y
	Y	- HV-transformers and cabling adequately isolated	Not required	N/A
	N	- equipment adequate protected against collision damage	Collision barriers to be considered	GJ Y
11 Process and/or equipment isolation	N	- easy access to manual isolation valves		GJ Y
	Y	- response time automatic isolation valves sufficient		N/A
	N	- fail safe isolation requirements met		GJ Y

12 Fire protection	Y	- hydrant available/accessible	Not required - falls under site risk assessment - firefighting facilities and wardens in area	N/A	
		- fire hose lengths adequate to reach equipment area			
		- fire extinguishers			
		- alarm system at or near equipment area			
		- automatic systems required			
		- fire detectors			
13 Equipment guards - protection shields/barriers	Y	- machine guards on rotating equipment	All moving parts enclosed in machine	N/A	
	N	- guard rails	Bump barrier needed where appropriate	GJ	Y
	Y	- bumper posts	Not required	N/A	
	Y	- oxygen flash protective shields/barriers	Not required		
	Y	- noise reduction	Equipment being installed in noise protection area		
14 Ventilation - air monitoring	N	- release of inert/toxic flammable gases possible	ATEX explosion valve	GJ	Y
	N	- present natural ventilation sufficient	Extraction system needed	GJ	Y
	N	- forced ventilation required	Extraction system needed	GJ	Y
	Y	- TLV values considered	Not required	N/A	
	Y	- monitoring required (e.g. O2 level)	No inert gasses being used		
	N	- local aspiration required	Masks (type) required as per area risk assessment	GJ	Y
	N	- locate to be maintained easily	Human factors (ergonomics) to be considered	GJ	Y
15 Access to control equipment	N	- install stationary ladder, platform, guardrails	Mezzanine platform being erected	GJ	Y
16 Labelling (piping, panels, etc.)	Y	process identification by labelling - chemical lines	Not required	N/A	
	Y	- process piping			
	Y	- high voltage identification			

	Y	- flammable storage			
	Y	- toxic storage			
17 Drawing updating	N	- construction drawing	To be provided by the designer	GJ	Y
	N	- P&I diagrams		GJ	Y
	N	- electrical diagrams		GJ	Y
	Y	- instrument loop diagrams	Not required	N/A	
	Y	- fire protection diagrams			
18 Warning signs, warning devices	Y	- mandatory signs in place : atmospheric hazard warning chemical hazard warning flammable product warning automatic machine start warning	Not required	N/A	
	Y	- back-up (power, instrument air)			
	N	- alarms and signalisation	Traffic system to be run in	GJ	Y
19 Environmental emissions/ Permits	Y	- noise within limit (industrial residential)	Complies with site limits	N/A	
	Y	- air emission control/testing; required permits available			
	Y	- water discharge	Not required	N/A	
	Y	- contamination municipal sewer possible contamination canals, etc. possible			
	Y	- permits available			
	Y	- contaminations of soil or groundwater possible			
	Y	- control of combustion equipment (boilers, etc.)			
	Y	- Spillage Control			
20 Hazardous waste	Y	- waste accumulation and quantity	Not applicable	N/A	
	Y	- permits required			

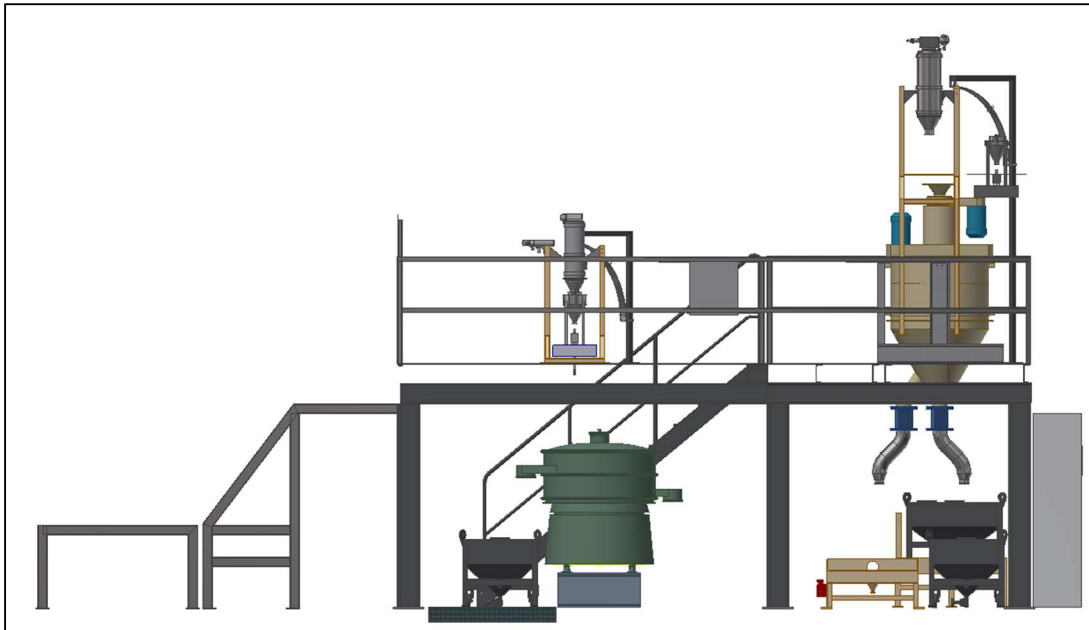
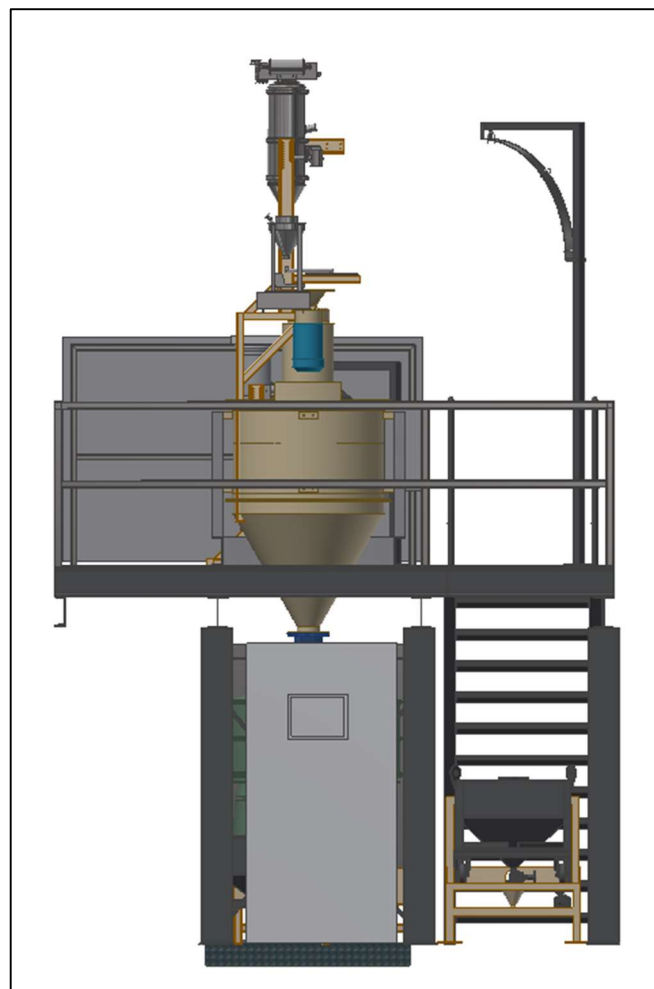
	Y	- storage and disposal procedures			
	Y	- disposal route according to law			
	Y	- disposal of non-hazardous			
21 Product or chemical spill control measures					
22 Access and Egress from buildings, enclosures, equipment	Y	- Exit doors not blocked by equipment or piping	Equipment being installed in existing manufacturing area which doesn't affect any compliance	N/A	
	Y	- equipment room doors equipped with panic bar			
	Y	- area lighting adequate, emergency lighting available			
	Y	- eliminate tripping hazards on exit routes			
	Y	- where required, stairs and/or permanent ladders provided to aid egress			
	Y	- two exits where necessary			
23 Tripping hazards	N	- conduits, pipes, valves, etc. not located in walkways	To be designed not to impact	GJ	Y
	N	- eliminate tripping potential		GJ	Y
	N	- floor opening covers level with grade		GJ	Y
	N	- storage does not protrude into walkways		GJ	Y
24 Sharp edges - protruding obstacles	N	- round off sharp edges or give protection	All works to be inspected	GJ	Y
	Y	- clearance on overhead pipes etc.	Not applicable	N/A	
	N	- valve handle direction away from persons	To be considered in designs	GJ	Y
25 Equipment lockout capability	N	- electrical	To be considered in designs	GJ	Y
	N	- mechanical		GJ	Y

26 Emergency shower/eye wash requirement	Y	- chemicals used requiring special wash	Site utilities to be utilised	GJ	Y		
27 Emergency procedure	Y	- emergency plans to be revised	No major change to operating process	N/A			
	Y	- special training required					
28 Operating procedure	N	- operating procedure to be revised	To be updated	GJ	Y		
	Y	- additional job training necessary	Not required	N/A			
	N	- safety aspects recognized	FMEA & risk assessment to be completed	GJ	Y		
	Y	- revision of pre-start and post stop instructions	Not affected	N/A			
	Y	- Workplace risk assessments/ Job Safety Analysis available or completed					
29 Contractors	Y	- selection	Apart of companies accepted register and have ISO9001 compliance	N/A			
	Y	- training	Competent workforce				
	Y	- co-ordination	Must have IOSH or NEBOSH qualification				
	Y	- supervision	Contractor to have own supervisor				
	Y	- work permits	To be issued as and when with RAMS				
30 Operators training	Y	- training should include but is not limited to:		N/A			
	Y	- start-up/shutdown procedure	As part of supervisors checklist				
	Y	- instrumentation on control method	Not required			N/A	
	Y	- operating temperatures and pressures					
	Y	- normal log control - i.e. daily temperatures/ pressures, etc.					
	Y	- confined space entry procedure	As part of site procedures			N/A	
	Y	- emergency procedures					
	Y	- alarms and shutdowns					
	Y	- vibration control	Maintenance activity			N/A	
	Y	- electrical isolation procedure					

31 Personal protection equipment	Y	- respirators	Area requirement	N/A	
	Y	- fire resistant clothing	Not required		
	Y	- chemical protecting garments etc			
32 Lifting devices	Y	- well balanced eyebolt or similar on equipment Warning : single point hoisting/lifting might overstress the lifting device, causing rupture	As part of operator onboarding training with pallet truck licenses	N/A	
	Y	- control weight restrictions and movement.			
	Y	- FLT training			
33 Control of constructors	N	- introduction training, incl. asphyxiation- and fire hazards	Inductions to be given prior to work	GJ	Y
	N	- work permit	To be issued as and when with RAMS	GJ	Y
	Y	- control of cranes	No cranes being used	N/A	
	Y	- product hazards	Not applicable		
	Y	- digging operation/excavations	Not needed		
34 Software Changes	Y	- Control loop changes	Not required	N/A	
	Y	- Addition or deletion of software modules			
	Y	- Restructuring of loops			
	Y	- New control loop			
	Y	- Putting loops on or off.			
35 Workplace Risk Assessment	Y	Review manufacturing area	As part of project documentation	N/A	

Table 24 - Management of Change for Installation

Appendix D – Layout Drawings

*Figure 73 - Front View Layout Drawing**Figure 74 - Side View Layout Drawing*

Appendix E – A1 Particle Size Distribution

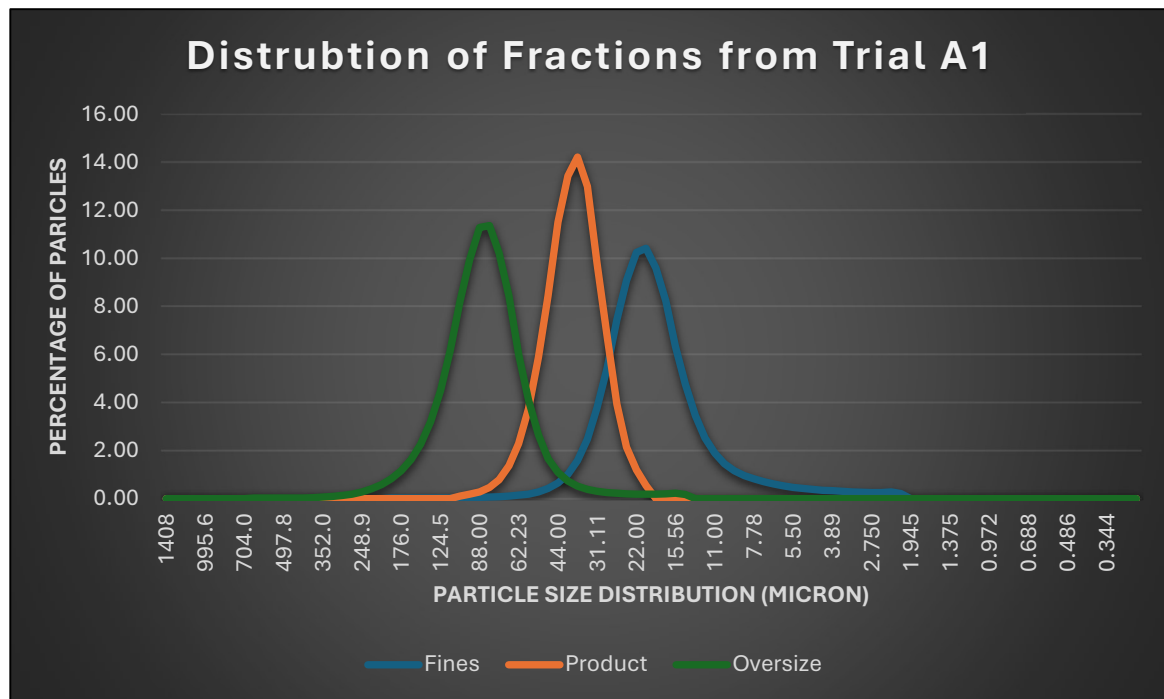


Figure 75 - Particle Size Distribution for Trail A1

Appendix F – A3 Particle Size Distribution

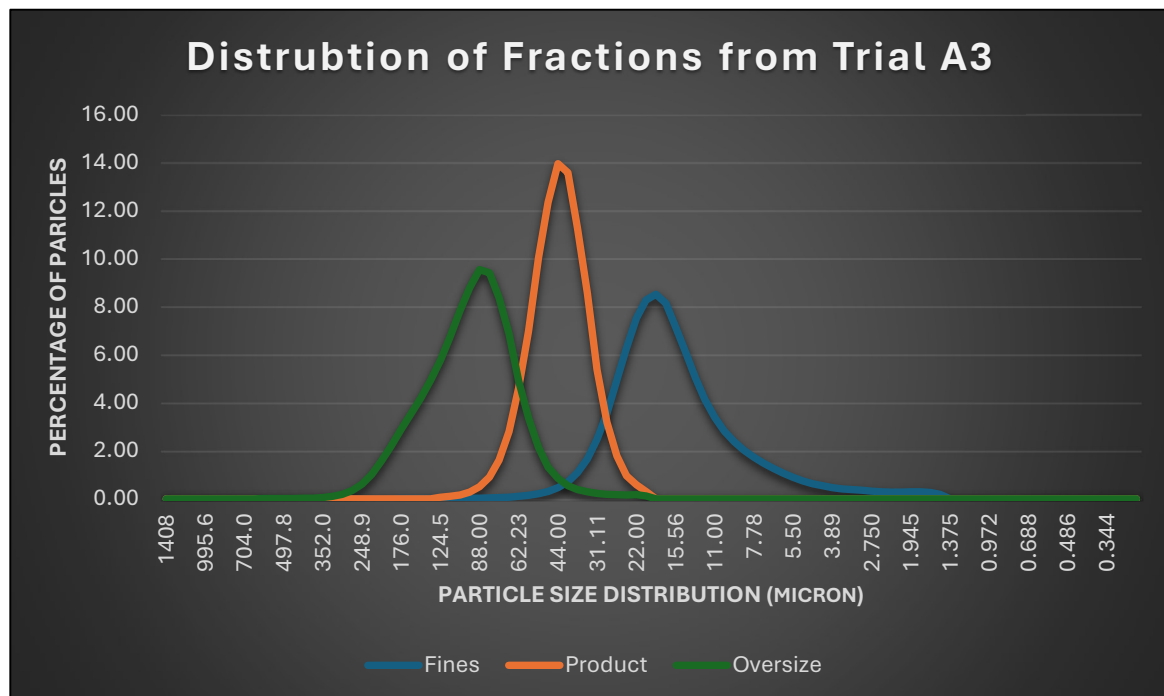


Figure 76 - Particle Size Distribution for Trail A3

Appendix G – A6 Particle Size Distribution

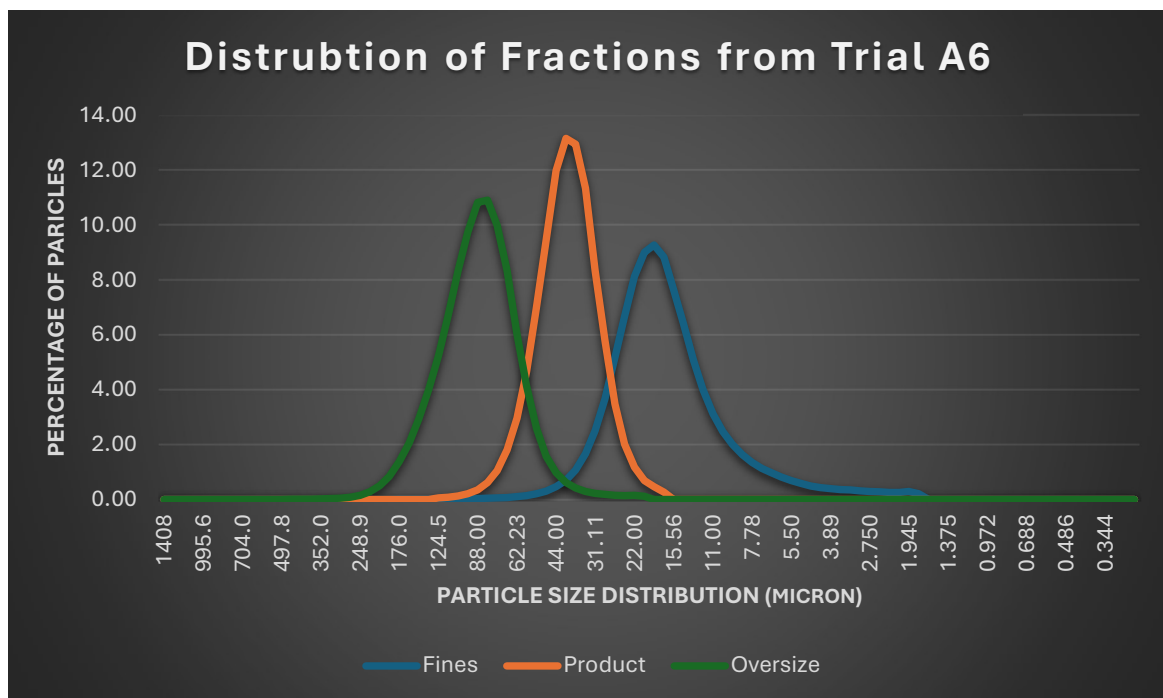


Figure 77 - Particle Size Distribution for Trail A6

Appendix H – B2 Particle Size Distribution

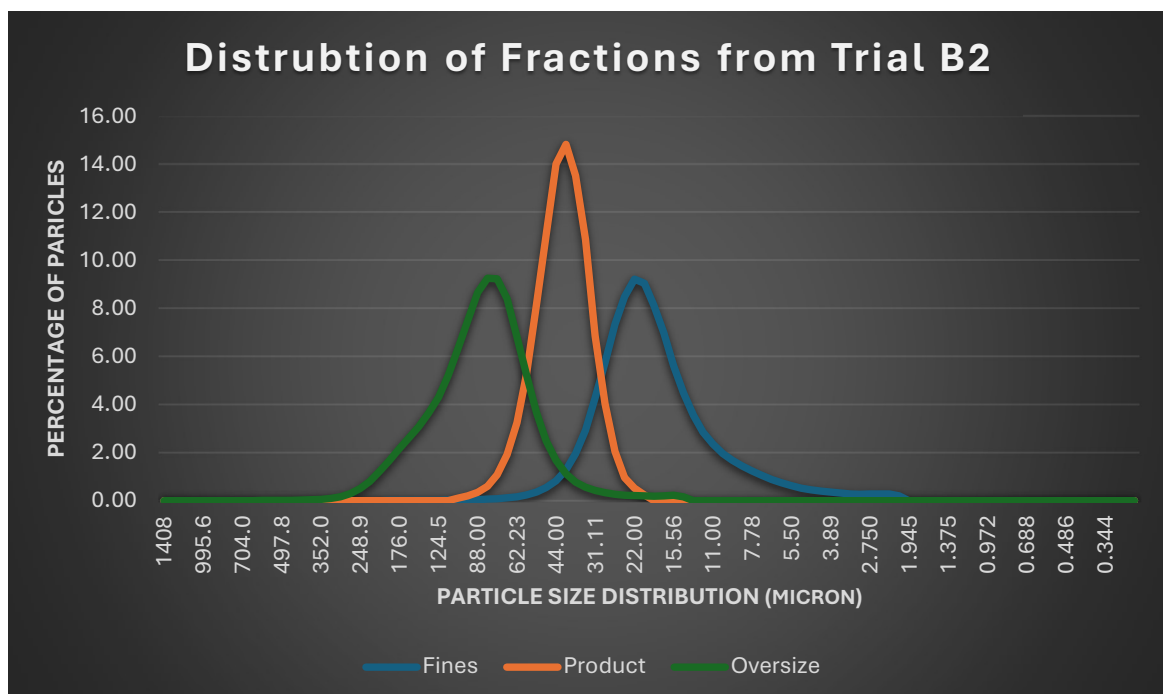


Figure 78 - Particle Size Distribution for Trail B2

Appendix I – B3 Particle Size Distribution

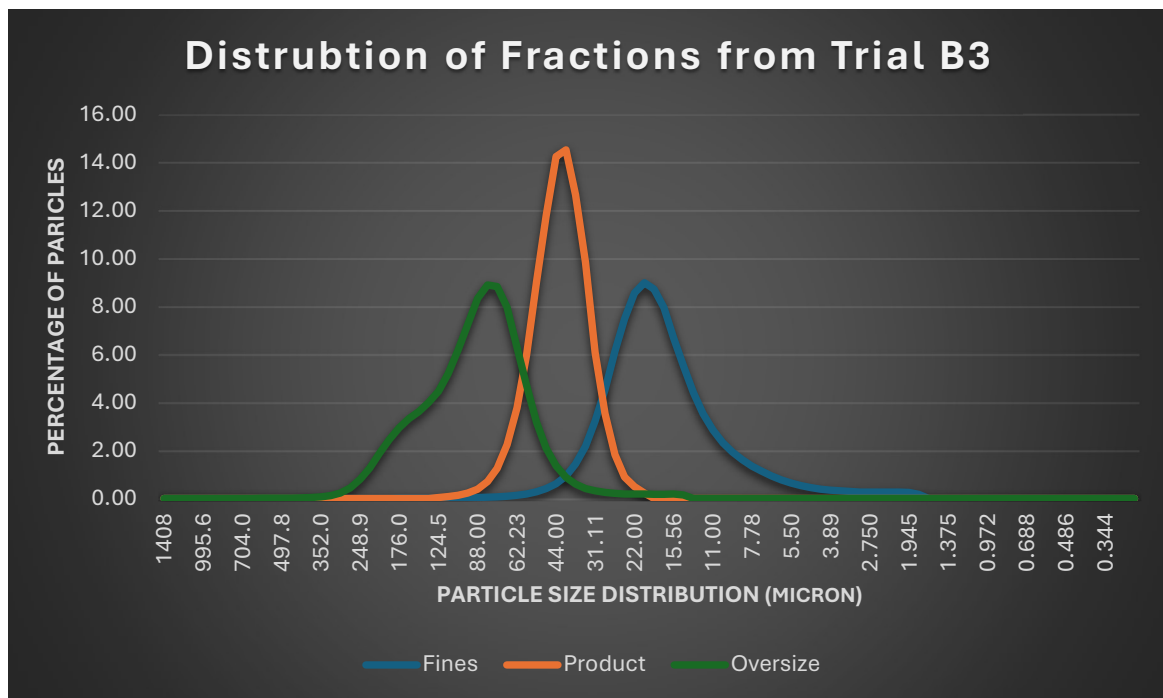


Figure 79 - Particle Size Distribution for Trail B3

Appendix J – B5 Particle Size Distribution

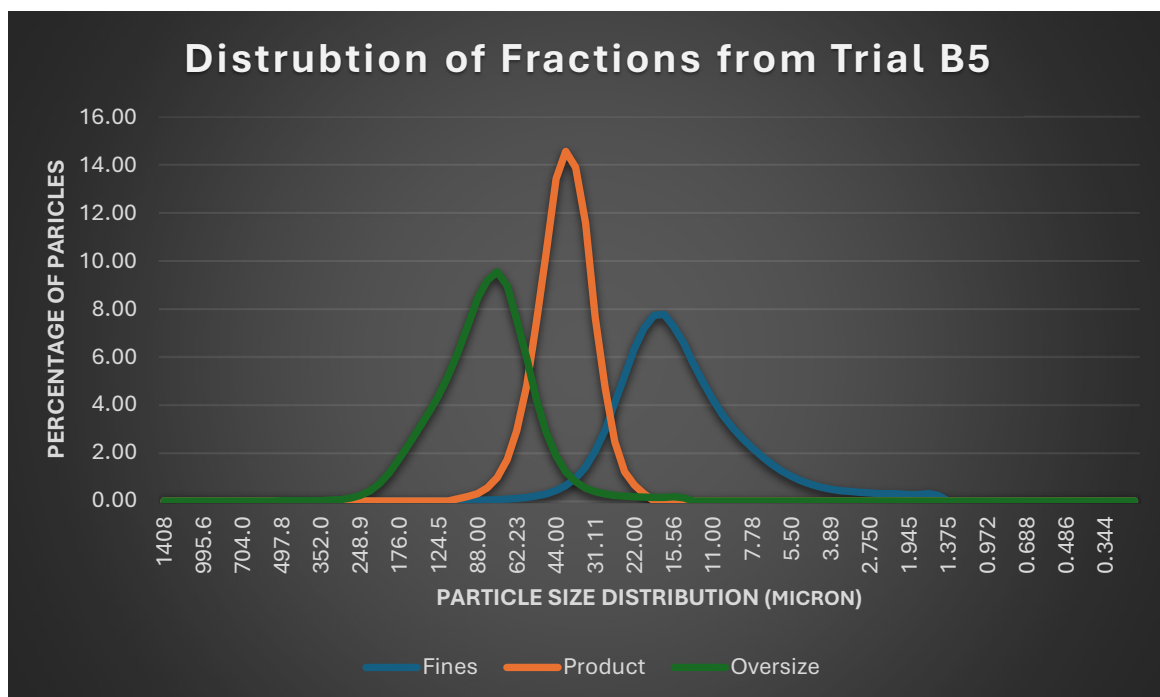
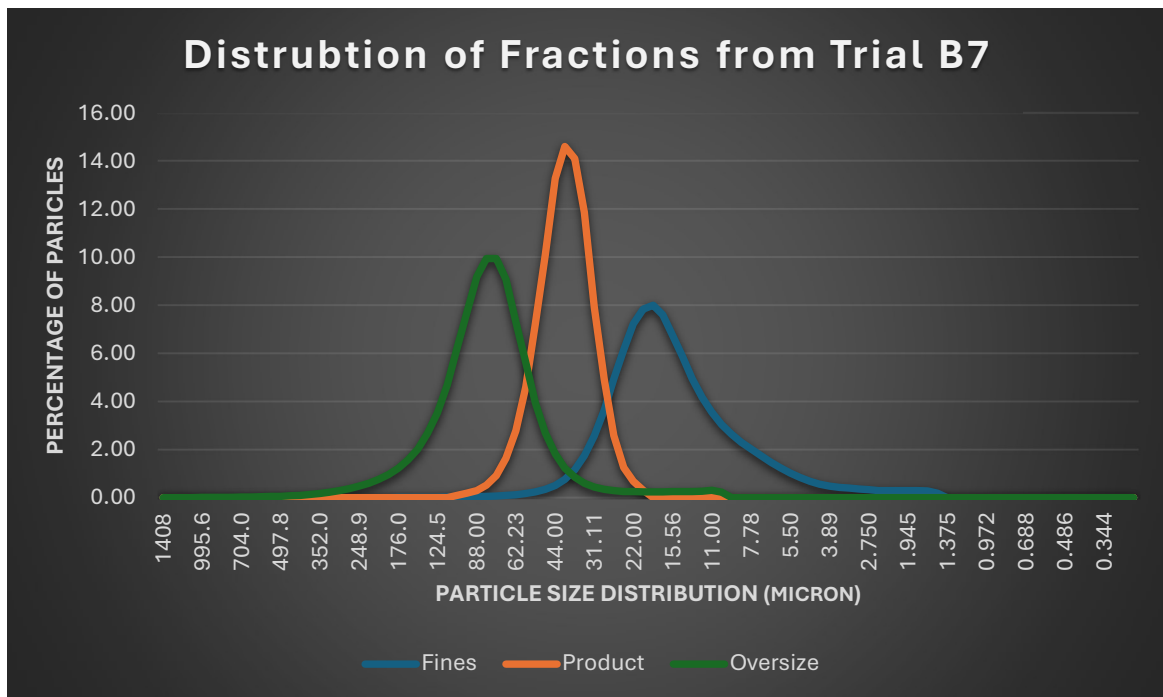


Figure 80 - Particle Size Distribution for Trail B5

Appendix K – B7 Particle Size Distribution

*Figure 81 - Particle Size Distribution for Trail B7*

Appendix L – A1 Screening Efficiency

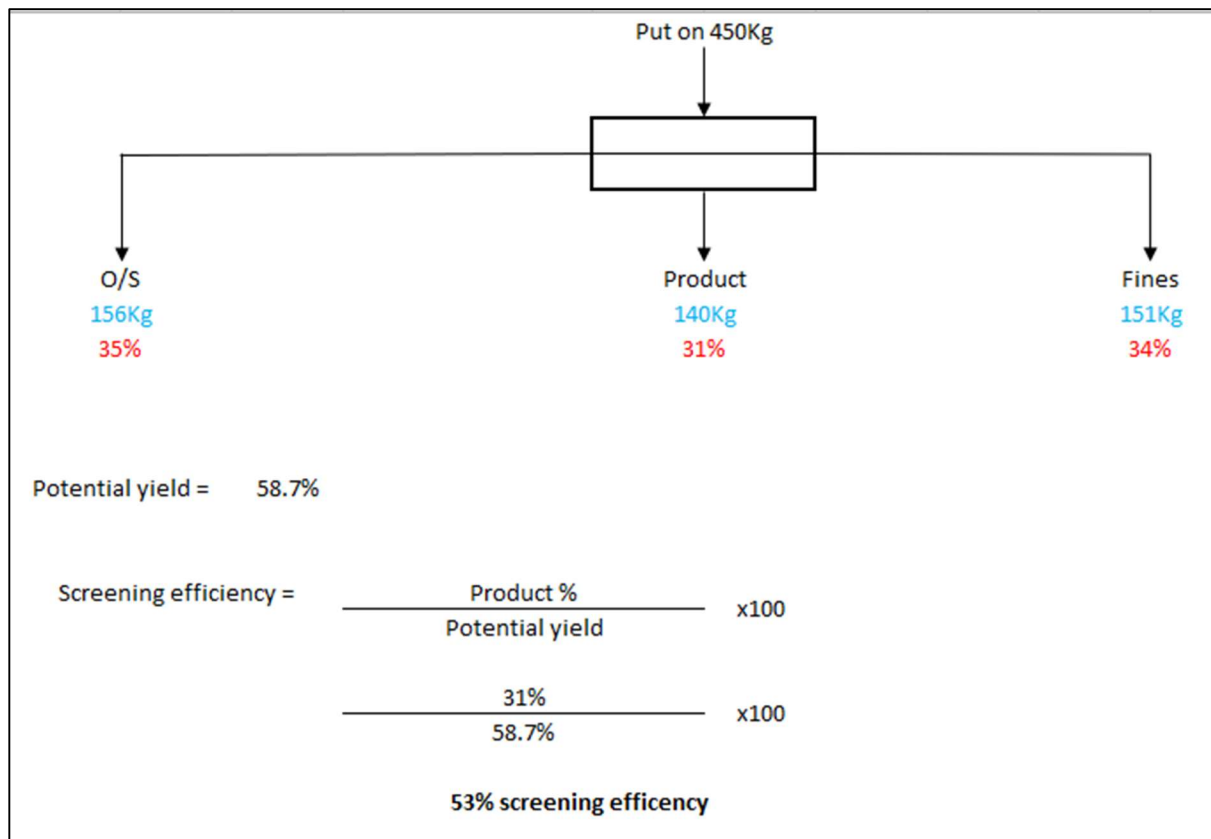


Figure 82 - Screening Efficiency for Trail A1

Appendix M – A3 Screening Efficiency

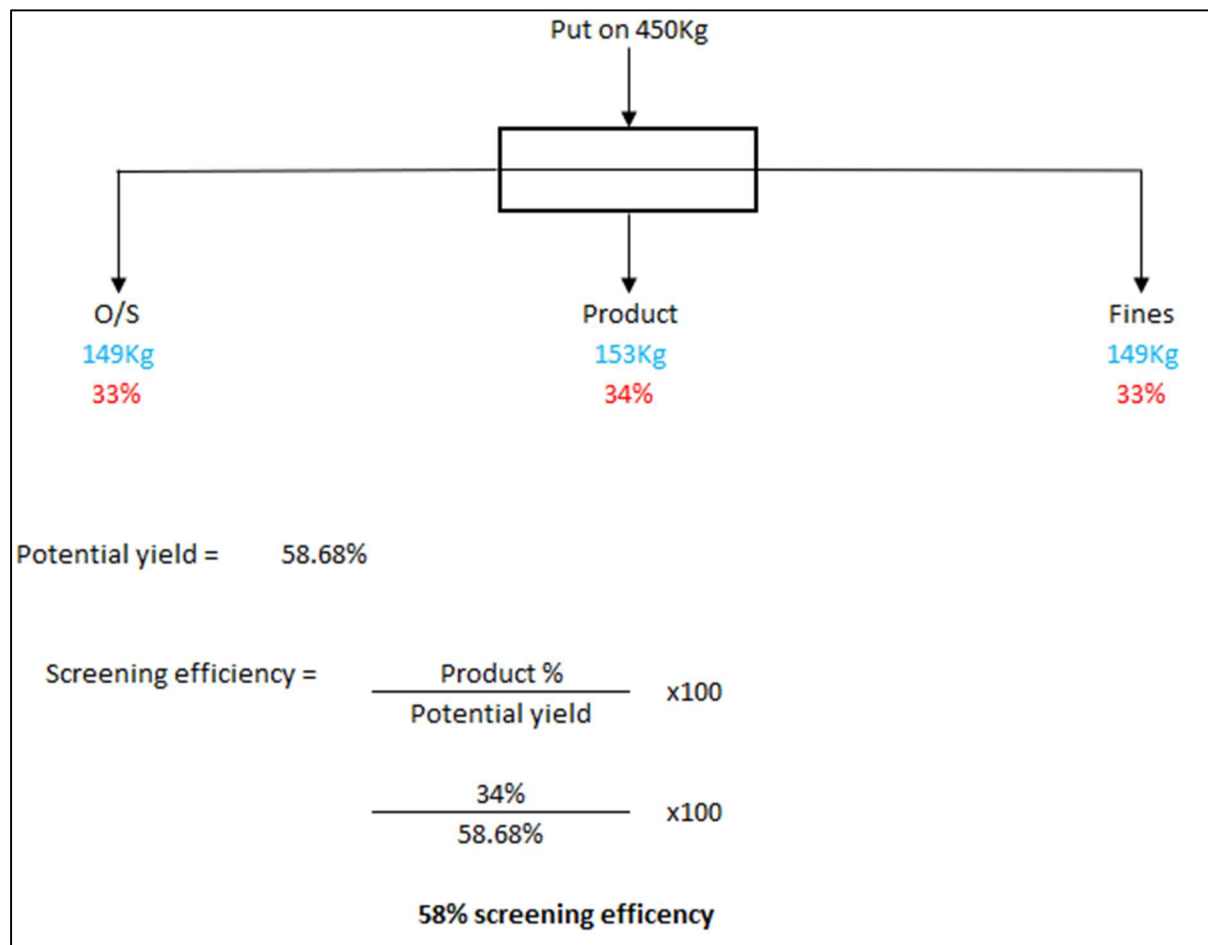


Figure 83 - Screening Efficiency for Trail A3

Appendix N – A6 Screening Efficiency

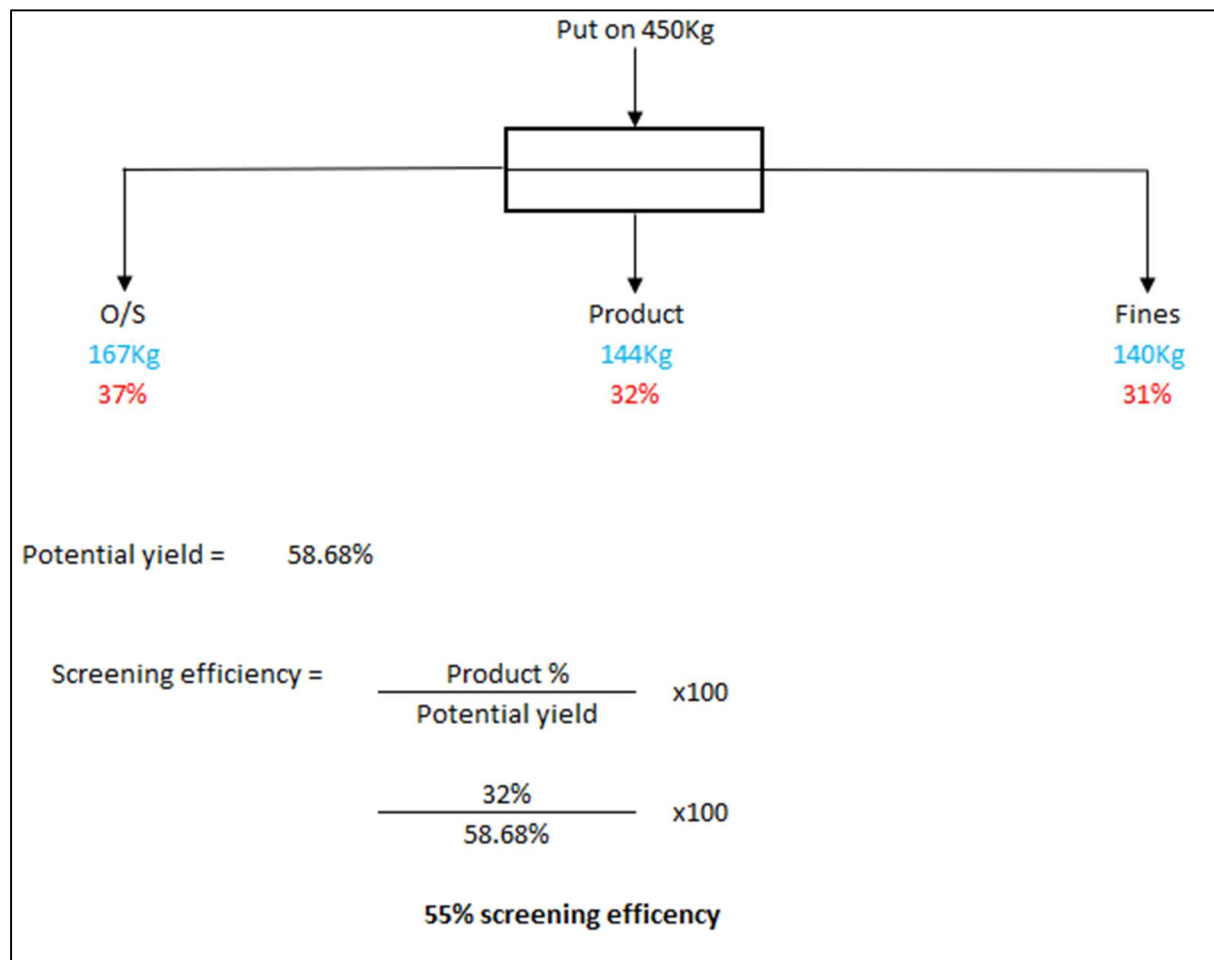


Figure 84 - Screening Efficiency for Trail A6

Appendix O – B2 Screening Efficiency

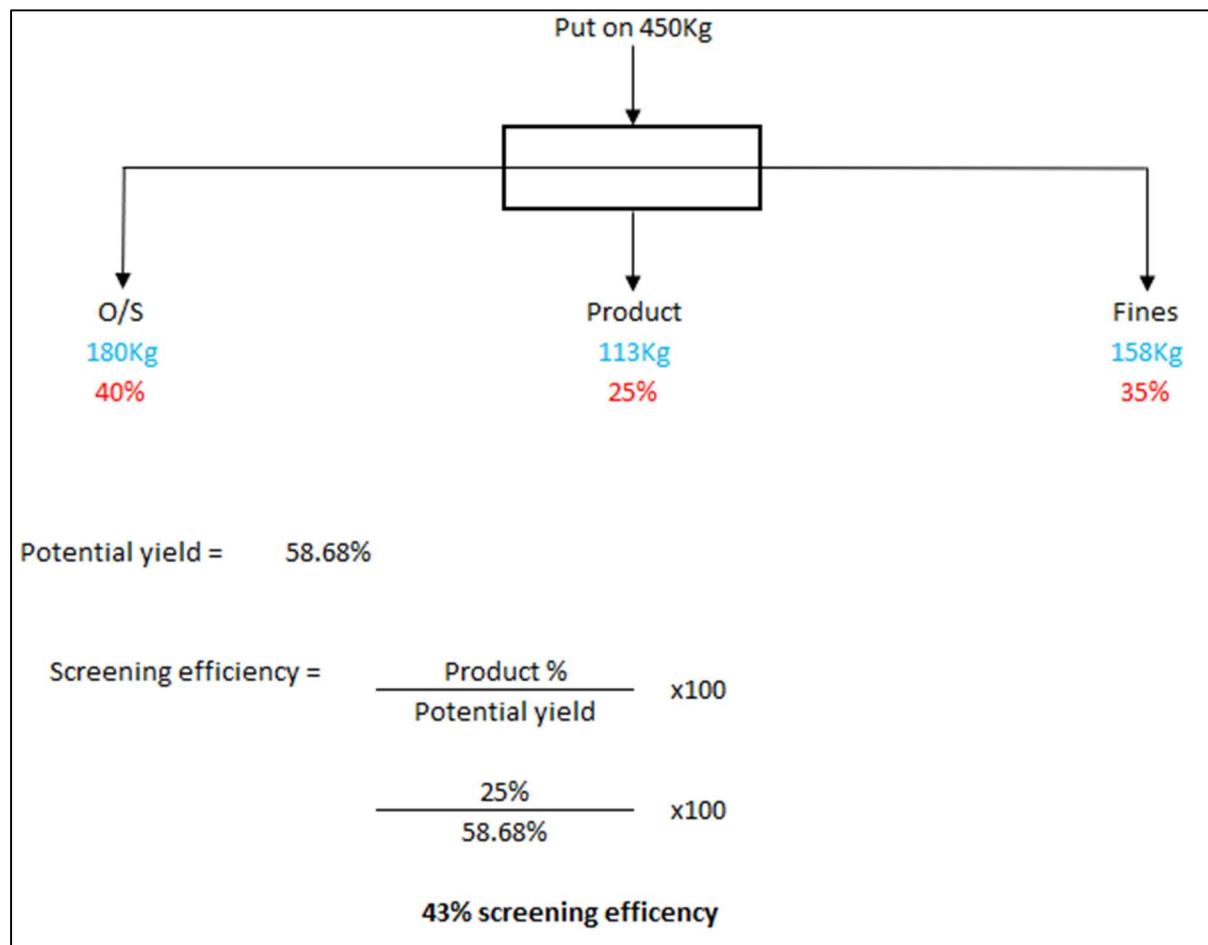


Figure 85 - Screening Efficiency for Trail B2

Appendix P – B3 Screening Efficiency

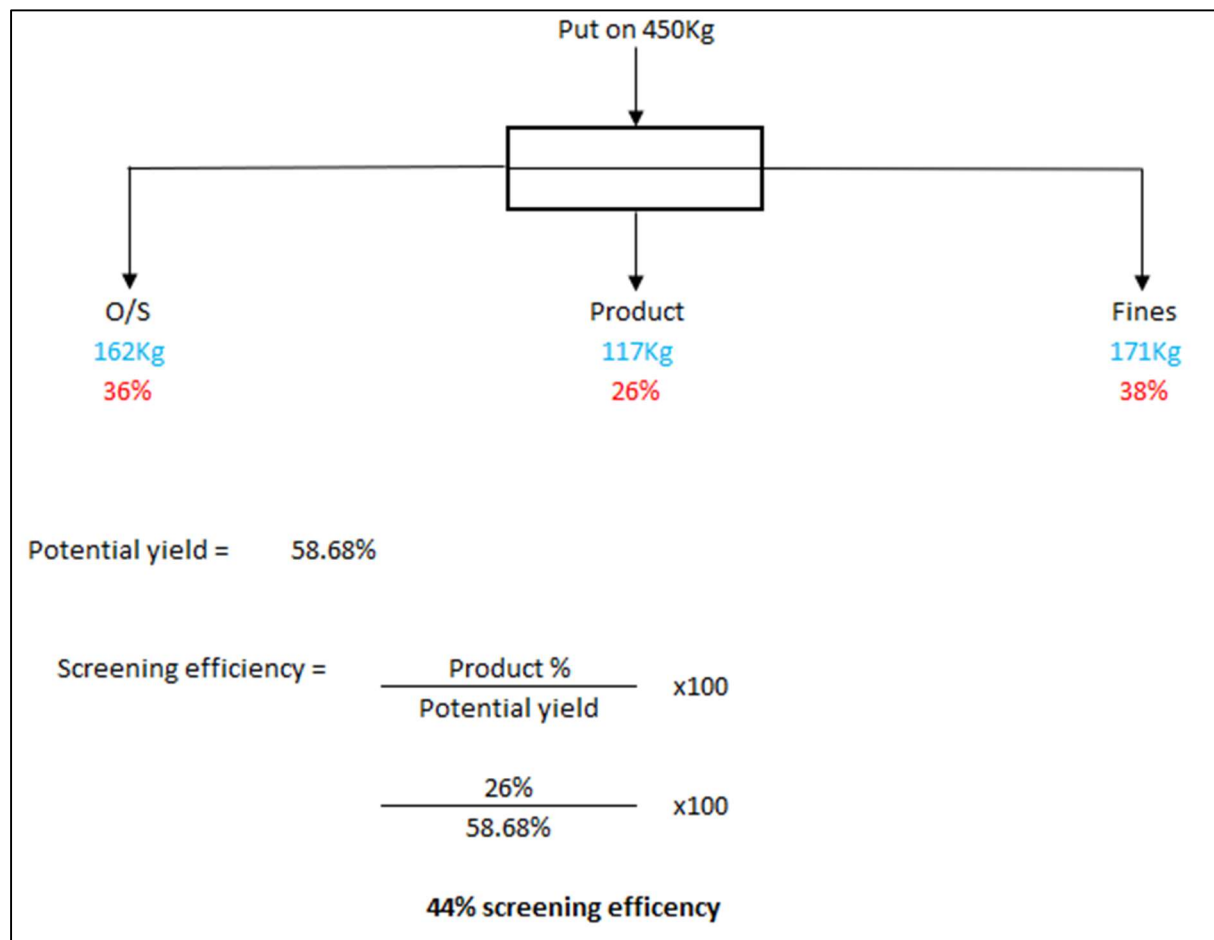


Figure 86 - Screening Efficiency for Trail B3

Appendix Q – B5 Screening Efficiency

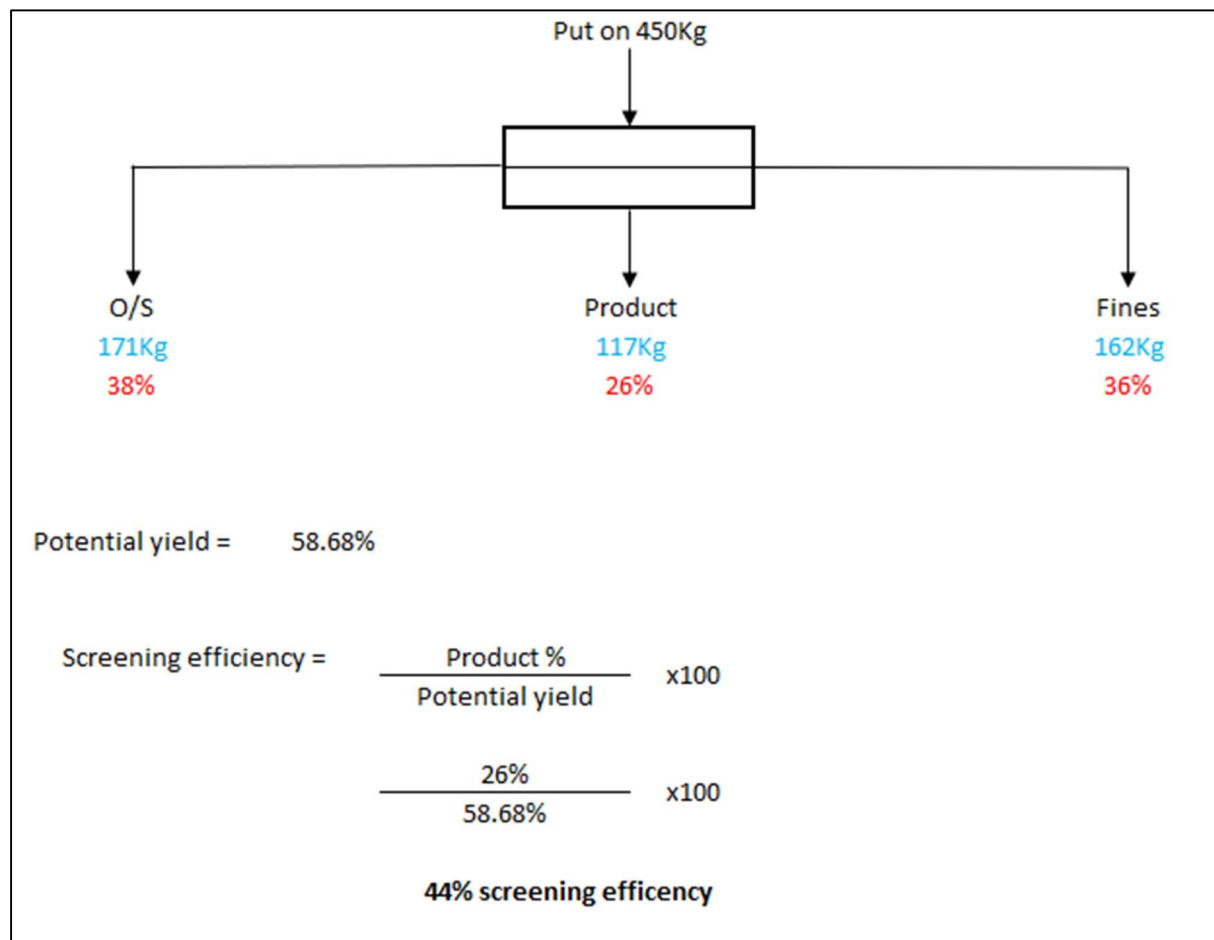


Figure 87 - Screening Efficiency for Trail B5

Appendix R – B7 Screening Efficiency

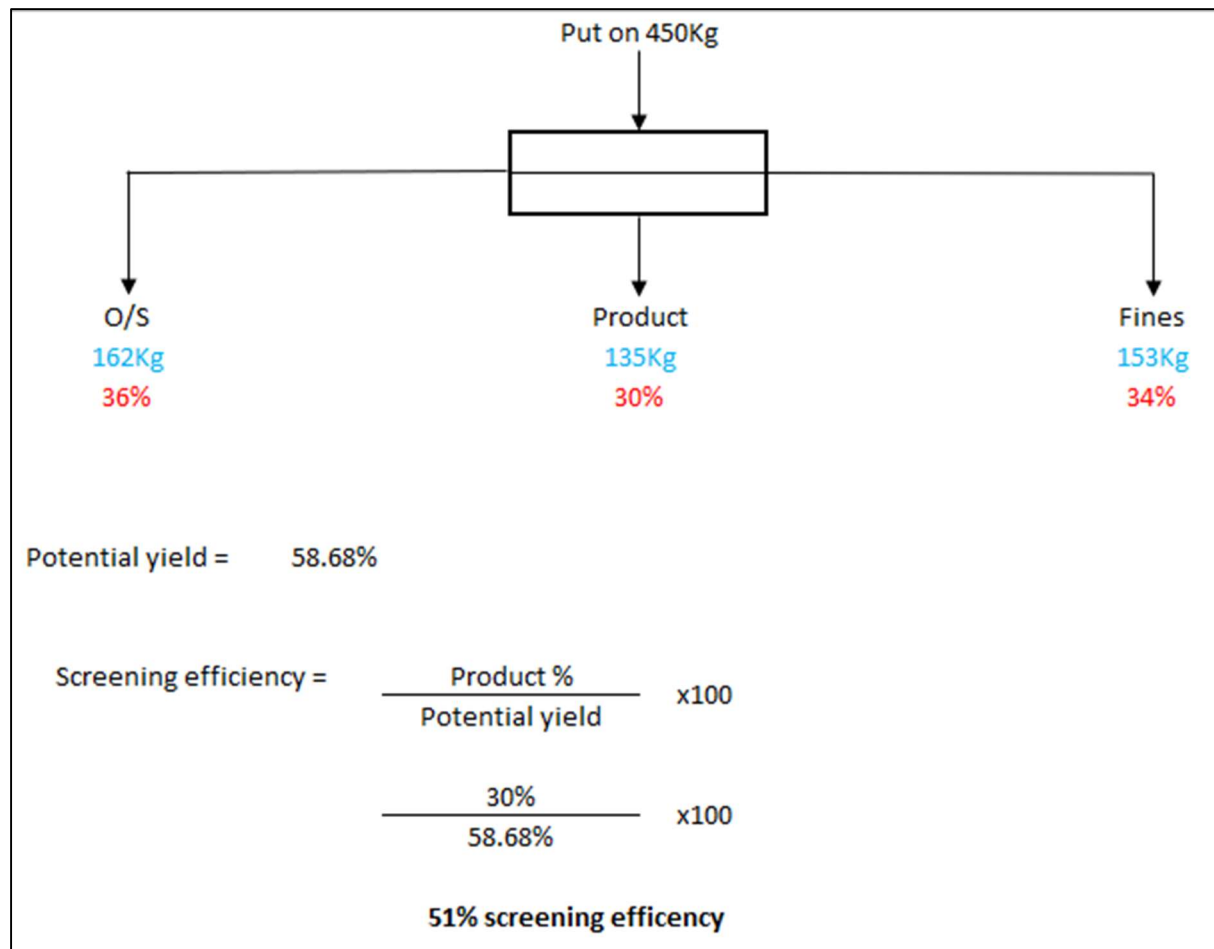


Figure 88 - Screening Efficiency for Trail B7