Design and Development of a Lean Phase Pneumatic Conveying System for Milk Powder in ATEX-Classified Zones: Elaboration of the User Requirement Specification

João Maria Barreirinho Mota

Master´s Dissertation

Advisor at FEUP: Prof. Flávia Barbosa
Advisor at the company: Mr. Nuno Silva

U. PORTO
FEUP FACULDADE DE ENGENHARIA UNIVERSIDADE DO PORTO

Master's in Industrial Engineering and Management

2025-06-27

Abstract

In today's industrial environment, where operational efficiency, safety and sustainability are becoming critical levers of competitiveness, the optimization of process systems is both a challenge and an opportunity. Pneumatic conveying systems, essential in many industries, must respond not only to functional requirements but also to increasingly stringent regulations and expectations for energy performance.

This dissertation presents the design and technical justification of a lean-phase pneumatic conveying system for milk powder, developed in response to safety and compliance challenges related to ATEX regulations. The project triggered a broader reassessment of the system's adequacy, performance and alignment with future production goals.

The work was structured into several stages: diagnosis of the existing system, evaluation of conveying technologies, definition of operating parameters and preliminary sizing of key components. A User Requirement Specification (URS) - a structured document consolidating technical, safety and integration requirements - was developed to guide supplier engagement and ensure alignment with industrial standards.

Pressure drop estimations, power demand calculations and a bottom-up investment assessment were conducted to validate the feasibility of the proposed solution. The redesigned system enables a significant capacity increase while promoting energy efficiency, operational safety and hygienic compliance.

The objectives of the project were accomplished and the outcomes demonstrate the value of structured engineering methodologies in supporting informed decision-making and sustainable industrial development.

Resumo

No contexto industrial atual, onde a eficiência operacional, a segurança e a sustentabilidade são fatores críticos de competitividade, a otimização de processos representa simultaneamente desafios e oportunidades. Os sistemas de transporte pneumático, essenciais em várias indústrias, devem responder não apenas a requisitos funcionais, mas também a regulamentações cada vez mais exigentes no que diz respeito a desempenho energético.

Esta dissertação apresenta o projeto e a fundamentação técnica de um sistema de transporte pneumático em fase diluída para leite em pó, desenvolvido em resposta a desafios de segurança e conformidade relacionados com regulamentos ATEX. O projeto motivou uma reavaliação mais ampla do desempenho e alinhamento do sistema com os objetivos futuros de produção.

O trabalho foi estruturado em várias etapas: diagnóstico do sistema existente, avaliação de tecnologias de transporte, definição de parâmetros operacionais e dimensionamento preliminar dos principais componentes. Foi elaborada uma *User Requirement Specification (URS)* - um documento estruturado que consolida os requisitos do projeto para orientar o processo de consulta a fornecedores e garantir o alinhamento com os padrões industriais.

Foram realizadas estimativas de perdas de carga, cálculos de potência e uma estimativa de investimento bottom-up para validar a viabilidade da solução proposta. O novo sistema permite um aumento significativo de capacidade, promovendo simultaneamente a eficiência energética, a segurança operacional e a conformidade higiénica.

Os objetivos do projeto foram alcançados, e os resultados obtidos demonstram a importância da aplicação de metodologias de engenharia estruturadas no apoio à tomada de decisão e ao desenvolvimento industrial sustentável.

Acknowledgements

First and foremost, to Eng. Nuno Silva, my supervisor at the company, for the opportunity to develop this project within such a prestigious organization as Nestlé, for the daily inspiration, and for all the support throughout these demanding yet enriching months.

To my supervisor at FEUP, Professor Flávia Barbosa, for the constant availability, valuable contributions to both content and structure, and for the trust shown since the very beginning.

To my family, who have always provided everything I needed to achieve my goals, and who are, without a doubt, the foundation of everything I am.

To my friends, who stood by me through every moment, and who, without even realizing it, inspire me every day to become a better version of myself. Being surrounded by such intelligent, ambitious and genuine people is a true privilege.

To my girlfriend, for being my motivation, for believing in me even more than I do, and for always being there with the right words and unwavering support.

Finally, to FEUP and University of Porto for these five memorable years. I have learned much more than engineering — I have learned to persist, to think critically, and to always believe in myself. I am ready for whatever lies ahead, proud of the path I have taken, and grateful for having lived one of the most meaningful chapters of my life.

Agradecimentos

Em primeiro lugar, ao Eng. Nuno Silva, orientador na empresa, pela oportunidade de desenvolver este projeto numa empresa tão prestigiada como a Nestlé, pela inspiração diária e por todo apoio ao longo destes meses exigentes e enriquecedores.

À minha orientadora na FEUP, a Professora Flávia Barbosa, pela constante disponibilidade, pelos contributos valiosos no conteúdo e na estruturação do trabalho, e pela confiança demonstrada desde o início.

À minha família, que sempre me proporcionou tudo o que necessitei para atingir os meus objetivos, e que é, sem dúvida, a base de tudo o que sou.

Aos meus amigos, que estiveram comigo em todos os momentos, e que, sem o saberem, me inspiram diariamente a querer ser melhor. Rodear-me de pessoas tão inteligentes, ambiciosas e genuínas é um verdadeiro privilégio.

À minha namorada, por ser a minha motivação, por acreditar mais em mim do que eu próprio, e por estar sempre presente, com uma palavra certa e um apoio incondicional.

Por fim, à FEUP e à Academia do Porto, por estes cinco anos memoráveis. Aprendi muito mais do que engenharia - aprendi a persistir, a pensar de forma crítica e a acreditar sempre em mim próprio. Saio daqui preparado para o que vier, com orgulho no caminho percorrido e consciente de que vivi uma das fases mais bonitas da minha vida.

"A winner is just a loser who tried one more time."

George M. Moore Jr

Contents

Acronyms and Symbols

URS	User Requirement Specification
IP	Ingress Protection
PLC	Programmable Logic Controller
HMI	Human-Machine Interface
FAT	Factory Acceptance Test
SAT	Site Acceptance Test
ATEX	Atmosphères Explosibles
SDGs	Sustainable Development Goals
GDP	Gross Domestic Product
AHU	Air Handling Unit
VFD	Variable Frequency Drive
RPM	Revolutions per minute
ROI	Return-on-investment
SHE	Safety, Health and Environment
$\dot{m}_{prod}$	Mass flow rate of the product [kg/h]
ρ_{produ}	Product's Density [kg/m^3]
d_p	Mean particle diameter [μm]
D	Internal pipe diameter [m]
$L_{horizontal}$	Horizontal pipe length [m]
$L_{vertical}$	Vertical pipe length [m]
N_{bends}	Number of 90° bends [–]
r_b	Bend radius [m]
T	Air temperature [°C]
ρ_{air}	Air density [kg/m^3]
P_{atm}	Atmospheric pressure [bar]
g	Gravitational acceleration [m/s^2]
A	Internal cross-sectional area [m^2]
π	Mathematical constant [–]
C_s	Minimum conveying air velocity [m/s]
C_1	Air conveying velocity [m/s]
Q_{air}	Volumetric air flow rate [m^3/s]
$\dot{m}_{air}$	Air mass flow rate [kg/s]
ϕ	Solids loading ratio [-]
$\Delta p_{\text{air-only}}$	Pressure loss due to air–pipe wall friction [Pa]
f	Darcy–Weisbach friction factor [–]
L_{eq}	Total equivalent pipe length [m]

Re	Reynolds number [–]
μ_{air}	Dynamic viscosity of air [Pa·s]
ε	Absolute roughness of the pipe's internal surface [m]
$\Delta p_{\text{total, Mills}}$	Total pressure drop in the conveying line [bar] or [Pa]
K	Empirical solids friction multiplier [–]
Δp_{solids}	Pressure drop due to solids friction [Pa]
C_s	Solids conveying velocity [m/s]
Δp_A	Pressure drop due to solids acceleration [Pa]
W	Solids line loading per unit pipe cross-sectional area) [kg/s·m^2]]
ρ^*	Effective density of the gas–solid suspension [kg/m^3]
Δp_G	Pressure drop due to vertical elevation of solids [Pa]
g_c	Dimensional constant for unit consistency [-]
$\Delta p_{\text{total, agg}}$	Total pressure drop from aggregated individual contributions [Pa]
p_2	Absolute pressure at the air mover outlet [Pa]
$P_{\text{isothermal}}$	Power required for isothermal air compression [kW]
P_{input}	Adjusted input power accounting for motor efficiency [kW]
$E_{\text{isothermal}}$	Daily energy consumption [kWh/day]
$\text{Cost}_{\text{isothermal}}$	Daily operating cost [€]
$\dot{V}_{\text{prod}}$	Volumetric flow rate of the product [m^3/h]
V_{rev}	Effective volume per revolution of the rotary valve [m^3/rev]
$V_{\text{theoretical}}$	theoretical volume per revolution [m^3/rev]

List of Figures

List of Tables

Chapter 1

Introduction

The industry sector, particularly the food industry, plays a pivotal role in Portugal's economic development, contributing significantly to the GDP (Gross Domestic Product), qualified employment and the country's export dynamics. In 2023, the national food sector recorded sales exceeding 17 billion euros, with exports experiencing robust growth, reinforcing the competitive position of Portuguese companies in international markets. (Instituto Nacional de Estatística, 2024)

In this increasingly demanding environment, operational excellence has become a fundamental pillar in modern manufacturing units, requiring an integrated approach in areas such as energy efficiency, industrial safety, sustainability and product quality. To address these growing demands, manufacturers must continuously reassess and optimize their production infrastructure. Safety is of particular importance in facilities handling combustible solid products, which are prone to forming potentially explosive atmospheres (ATEX).

Among the many technologies employed in solids handling operations, pneumatic conveying systems have gained prominence due to their enclosed design and operational flexibility. However, adapting these systems to such environments requires technologically robust solutions that are properly dimensioned and compliant with the applicable legal and regulatory requirements. These systems are widely used in the food industry due to their ability to preserve product characteristics, optimize internal flows and ensure high standards of hygiene and safety.

This dissertation is set within this context and was developed at Nestlé's industrial unit in Avanca, a factory with high technical and production complexity. The project focused on redesigning a pneumatic conveying system for powdered milk, aiming to eliminate a risk identified in an external ATEX assessment, improve system performance and ensure technical and legal compliance. This intervention is particularly significant for the organization, not only due to its immediate operational impact but also as a reflection of the company's culture of continuous improvement and industrial excellence.

Nestlé, established over 150 years ago, is the world's largest food and beverage company. Headquartered in Switzerland, it operates in 185 countries, has more than 350 factories across 75 countries and holds a vast portfolio of more than 2,000 brands (Nestlé S.A., 2025). Nestlé has been present in Portugal since 1923, with its operations comprising two manufacturing units: one located in Porto and another in Avanca (Aveiro). The portuguese headquarters, based in Lisbon, is supported by a national distribution center in Aveiro and five commercial branches spread across mainland Portugal and the islands. In 2023, Nestlé Portugal recorded a turnover of 711 million euros, representing a 5.5% growth compared to 2022 (Nestlé Portugal, 2024).

This dissertation project was carried out in the Technical Services department of the Avanca factory, which is a multicategory factory with around 450 employees and is considered a center of excellence in the manufacturing of food products for human consumption, using both animal and plant-based raw materials.

The facility includes several production sectors, such as:

- Instant cereal-based beverages;
- Nutrition for infants and adults;
- Breakfast cereals;
- Powdered milk;
- Dry-mixed foods.

In addition to its core food production activities, the factory also supports several complementary and auxiliary operations, including: technical maintenance, logistics, quality control laboratories and administrative functions.

At this manufacturing site, as represented in Figure 1.1, each production sector is managed by a Production Manager who reports to the Factory Manager. The Factory Manager also oversees the Technical Services Manager, the Safety, Health and Environment Manager, the Distribution Center Manager, the Quality Manager, the Physical Logistics Manager and the Administrative Services Manager.

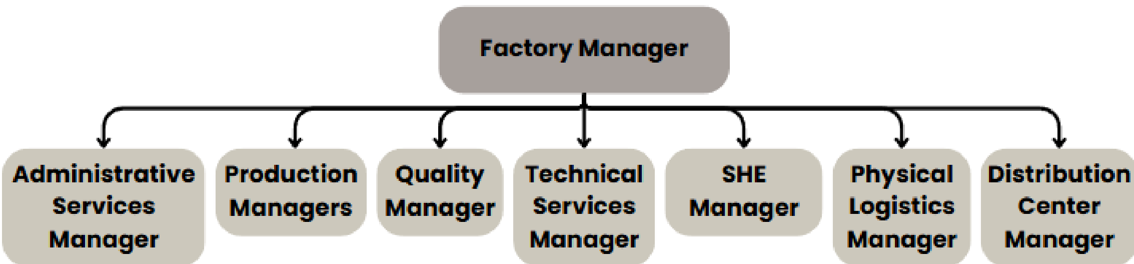

Figure 1.1: Factory organizational chart

The Technical Services department is composed of maintenance managers, one IT manager, project and investment engineers and an asset management coordinator. Each maintenance manager is supported by maintenance team leaders and several technicians (mechanical, electrical, instrumentation and automation specialists), as shown in Figure 1.2. The Technical Services department is responsible for supporting the production teams, whether in troubleshooting or implementing improvements. In addition, the department is also responsible for planning and monitoring corrective and preventive maintenance activities for equipment, managing stock control of parts and materials required for maintenance and overseeing general services management (such as steam generation, compressed air and wastewater treatment).

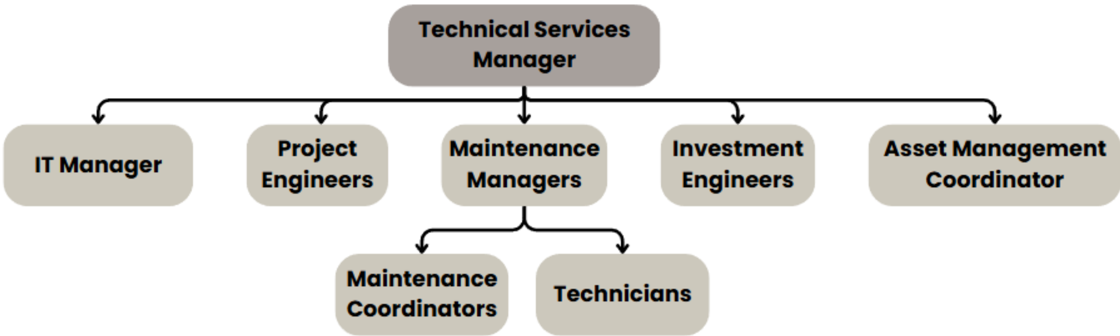

Figure 1.2: Technical Services organizational chart

In alignment with these responsibilities, this project was developed with the objective of proposing a technically and economically viable solution for the implementation of a new pneumatic conveying system for powdered milk, suited to the production needs and compliant with the required standards. To achieve this, the following specific objectives were defined:

- Evaluate the performance of the current powdered milk conveying system (efficiency, failures, safety, product quality);
- Analyze the properties of the various types of products in order to obtain the necessary data for the design of a new pneumatic conveying system;
- Review existing pneumatic conveying technologies, with emphasis on dilute phase and dense phase solutions;
- Determine the most relevant criteria for selecting the type of system best suited to the factory context;
- Perform the design of the new system, defining the process parameters and required equipment and develop a User Requirement Specification to request quotations from suppliers;
- Outline the expected investment and operational costs to support implementation decisions.

Building on these objectives, the approach adopted for the development of the project followed a structured and sequential logic, enabling a progressive analysis of the problem and the formulation of an appropriate solution tailored to the factory's context. The flowchart presented in Figure 1.3 outlines the main phases and tasks carried out throughout the project, highlighting the logical interdependence between activities. The process began with the analysis of an external consultancy report, which served as the foundation to understand the potential hazards associated with the current installation. Simultaneously, relevant legal frameworks and guidelines were studied and information regarding the production processes was gathered to ensure that all technical decisions would be aligned with operational, safety and environmental requirements. This was followed by the evaluation of the current pneumatic conveying system, during which failure evidence, relevant powder characteristics and physical installation constraints were collected. These data were essential for critically assessing the existing solution and guiding the selection of a more suitable technology.

In parallel, an in-depth study of pneumatic conveying technologies was conducted, comparing dilute/lean versus dense phase systems, as well as positive versus negative pressure modes. Based on this study and considering the specificities of the process, the most appropriate transport mode was selected. This informed the elaboration of the URS, a structured document consolidating all technical, functional, regulatory and integration requirements. Once the URS was defined, the preliminary dimensioning of the main system components was carried out, aiming to validate the feasibility of the proposed solution. Finally, a preliminary investment and cost overview was conducted, providing a general perspective on the expected expenditures and strategic benefits of implementing the proposed system.

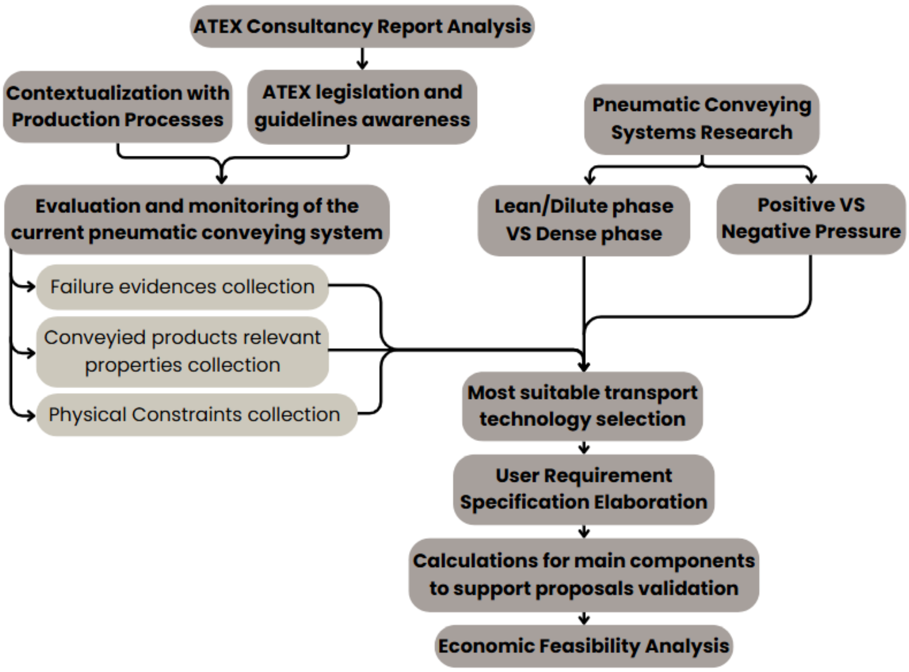

Figure 1.3: Project methodology flowchart.

To provide a clear and comprehensive account of the work carried out, the dissertation is organized into five chapters.

Chapter 1 introduces the project context, presents the identified problem, defines the main objectives and describes the methodology and organization adopted throughout the project.

Chapter 2 presents the literature review, covering general considerations on pneumatic conveying, the main system types and modes of operation, the influence of particle properties on transport behavior and the key components involved in such systems.

Chapter 3 provides a more detailed explanation of the problem, contextualizing it within the general production process. It also describes the origin of the project, which emerged from a technical consultancy focused on compliance with European directives and standards to equipment operating in potentially explosive atmospheres. These regulatory frameworks served as the basis for the diagnosis of the problem and the need for technical intervention.

Chapter 4 focuses on technical analysis and system design. It presents the rationale behind the choice of system type and operating mode, explains the process followed for defining the User Requirement Specification and details the design calculations for the system's most critical components. A preliminary investment estimate based on a bottom-up approach is also included.

Finally, Chapter 5 summarizes the main conclusions of the study, proposes potential improvements and directions for future work and discusses how the proposed solution contributes to the United Nations Sustainable Development Goals (SDGs), reinforcing its relevance in the context of sustainability and safety in the food industry.

Chapter 2

Literature Review

2.1 General Considerations

In food process engineering, unit operations are the foundational steps through which raw materials are transformed into finished products. Among these operations, the transportation of solid materials, such as powders and granules, is critical to the efficiency and safety of the production process (Fellows, 2009). These materials are often fragile or sensitive to contamination, which demands systems that ensure both gentle handling and hygienic standards - especially in the food industry (Malekjani and Jafari, 2023).

Pneumatic conveying emerged as a highly effective technology for transporting powders using pressurized air or gas within enclosed pipelines. This method has gained widespread application due to its ability to preserve product quality while reducing the risks of contamination and material loss (Mills, 2016). Compared to mechanical conveying systems such as screw or belt conveyors, pneumatic systems are particularly advantageous in environments where hygiene and flexibility are essential (Rhodes, 2008).

Historically, the development of pneumatic conveying systems dates back to the late 19th century, with early applications in the cement and grain industries. Over time, these systems evolved through empirical experimentation and later through analytical and computational modelling approaches, including the application of fluid mechanics and particle physics (Klinzing et al., 2010). The introduction of specialized components such as rotary valves, blowers and airlocks allowed for better control of flow and pressure, enabling reliable operation under various material conditions.

In today's context, pneumatic conveying systems are broadly used in sectors like pharmaceuticals, plastics and especially food processing. In this last case, they are essential for moving ingredients like milk powder, sugar, cocoa, or flour between processing stages, while complying with increasingly strict sanitary regulations. Moreover, automation and control integration have turned these systems into vital elements in ensuring traceability and quality assurance across the production line (Mills, 2016).

2.2 Pneumatic Conveying – General Principles, Advantages and Disadvantages

Pneumatic conveying is a method of transporting bulk solid particles through an enclosed pipeline using a gas stream, most commonly compressed air. The movement of solids occurs due to the application of a pressure differential between the feed and discharge points, allowing the gas to suspend and carry particles across the system. As Mills (2016) explains, this transport mechanism depends on the balance of forces acting on the particles - namely drag, gravity and pressure gradient - and is influenced by factors such as particle size, density and air velocity.

Although conveying regimes will be addressed in detail in subsequent sections, it is important to note that these systems can operate in different flow patterns, determined by particle concentration and velocity. Klinzing et al. (1987) classifies these broadly as dilute or dense phase conveying, although transitions between regimes are continuous rather than sharply defined. The choice of conveying regime has implications on system design, energy requirements and product integrity.

One of the main advantages of pneumatic conveying lies in its reduced number of mechanical components compared to traditional mechanical conveyors, which simplifies maintenance and enhances operator safety. Pipeline routing flexibility is also a key benefit since conveying pipelines can be run vertically, horizontally or around existing equipment. They are particularly suitable for space-constrained facilities. Furthermore, their integration with automation and process control systems makes pneumatic conveyors ideal for use in continuous production environments (Rhodes, 2008).

Despite these advantages, pneumatic conveying presents important challenges. According to Klinzing et al. (2010), the energy consumption required to compress and move air is often higher than that of mechanical alternatives. This impact is more significant in long-distance conveying or systems operating under high pressure.

Product degradation is also a concern. Fragile materials can suffer damage from high-velocity impacts with pipeline walls or bends, while abrasive products may cause erosion of internal surfaces over time (Mills, 2016). Scheibel (2018) further emphasizes the need for careful pipeline design and flow regulation, as poor control may lead to blockages, surging, or excessive wear. Table 2.1 summarizes the main advantages and disadvantages of these types of systems.

Table 2.1: Advantages and Disadvantages of Pneumatic Conveying Systems

Advantages	**Disadvantages**
Closed systems can reduce contamination	High energy consumption due to compression
Low maintenance due to fewer moving parts	Product degradation from velocity impact
High layout flexibility	Pipeline erosion with abrasive materials
Operator safety	Risk of blockages if not properly sized
Easily integrated into control systems	Not ideal for all materials (e.g., very cohesive powders)

While the general features described here apply to most pneumatic conveying systems, their specific configuration and performance vary considerably depending on how the system is designed and operated. Key factors influencing system selection include whether the conveying process is carried out under positive or negative pressure, and whether the system is open, closed, or a combined configuration. These variations impact not only the energy requirements and flow characteristics but also aspects such as dust control, safety, and integration with surrounding equipment. A more detailed discussion of these system types is presented in the following section.

2.3 System Types and Modes of Operation

2.3.1 Classification by Conveying Phase

Pneumatic conveying systems are generally divided into dilute (or lean) phase and dense phase regimes. In dilute phase, the particles are fully suspended in the gas stream and transported at high velocities - typically above 15 m/s. This setup is ideal for light, free-flowing powders and while it is flexible and relatively simple to control, it often leads to increased pipeline wear and product degradation due to particle collisions (Mills, 2016). In contrast, dense phase conveying operates at lower air velocities and higher material loading, causing the product to move in plugs or slugs through the pipe. Klinzing et al. (2010) describes several dense phase flow patterns, each with unique pressure and flow characteristics. Figure 2.1 illustrates typical particle arrangements during dense phase conveying.

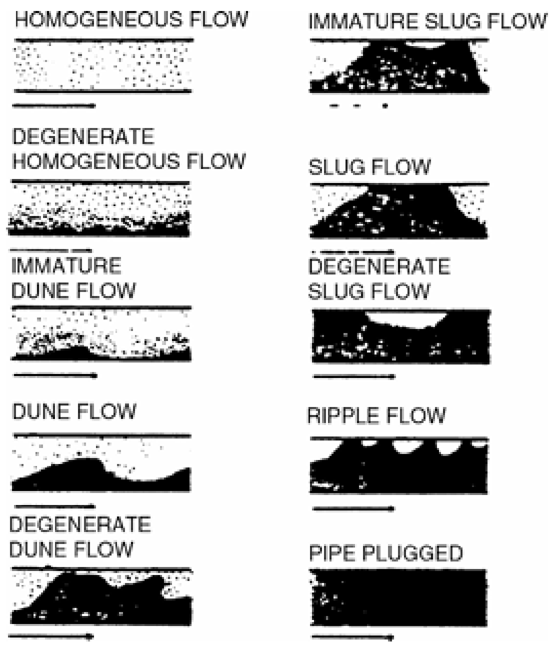

Figure 2.1: Examples of particle flow patterns (Klinzing et al., 2010).

2.3.2 Classification by Operating Pressure

In positive pressure systems, air is blown from the feeding point using an air mover, pushing the material downstream to the receiving hoppers. According to Rhodes (2008), this is the most common configuration in industrial settings, especially for dilute phase systems conveying over long distances. A schematic example of this setup is shown in Figure 2.2.

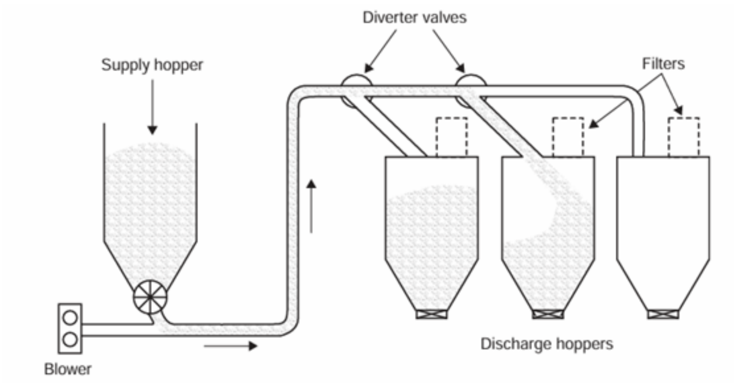

Figure 2.2: Typical positive pressure conveying system (Mills, 2016).

Alternatively, negative pressure systems, or vacuum systems, pull the material through the pipeline using suction generated at the receiving end. These systems are particularly suited for hygienic applications or configurations requiring multiple pick-up points. As Mills (2016) notes, they are often limited to short-to-medium distances due to pressure losses. A typical negative pressure layout is shown in Figure 2.3.

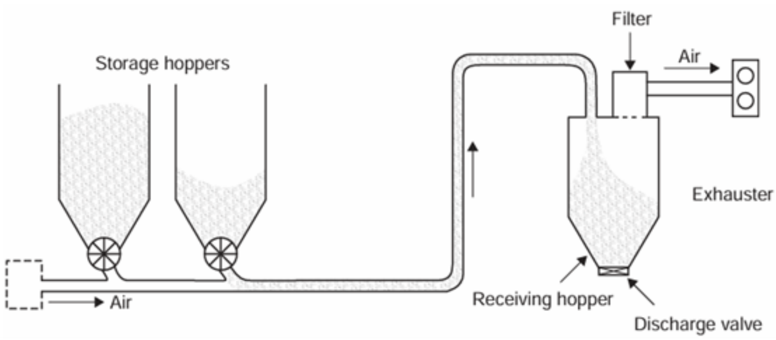

Figure 2.3: Typical negative pressure conveying system (Mills, 2016).

A third option, illustrated in Figure 2.4, is the combined pressure system, which uses vacuum in the initial section and overpressure in the final section of the pipeline. This configuration is suitable for long or complex transfer lines and helps to balance flow control and energy efficiency.

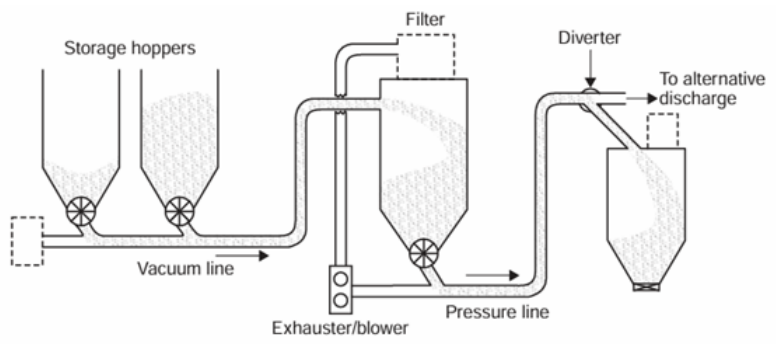

Figure 2.4: Typical combined vacuum and pressure conveying system (Mills, 2016) (Modified).

2.4 Influence of Particle Characteristics on Pneumatic Conveying

2.4.1 Key Properties and Their Impact

The behavior of bulk solids during pneumatic conveying is significantly influenced by a combination of physical, mechanical and dynamic particle properties. Among the most relevant are particle size, density, abrasiveness, friability, cohesion and hygroscopicity. These characteristics affect product flowability, system wear, degradation during transport and the air velocity required for suspension and movement.

Particle size and density are particularly decisive, as they determine the minimum conveying air velocity and whether a material can be transported in dilute phase. According to Mills (2016), the conveying air velocity must exceed the saltation velocity to avoid particle settlement. Conversely, in dense phase systems, it must remain below the choking velocity to ensure continuous flow without pressure surges or blockages.

Abrasiveness is another critical property, especially when conveying hard or angular solids. According to Klinzing et al. (2010), particles such as silica or glass beads can erode pipe walls, elbows and feeding devices. Material selection for contact surfaces - whether stainless steel, polymers, or ceramic coatings - depends largely on expected abrasion intensity.

Friability, or the tendency to fracture under stress, is directly related to particle degradation. Degradation arises both from impacts with pipeline bends and from interparticle collisions. This leads to fines generation and potential changes in solubility or fluidity, especially critical in food products. The degradation intensity increases exponentially with conveying velocity, reinforcing the need for precise speed control (Klinzing et al., 2010).

Cohesion and hygroscopicity also complicate transport. Cohesive materials may form rat holes or bridges, requiring external agitation or vibration. Hygroscopic powders, on the other hand, absorb moisture from the conveying air, leading to caking, stickiness, or fouling of the filter. According to Gomide (1983), even small changes in air humidity or temperature can drastically alter the flow behavior of some materials. Hygroscopic powders may absorb moisture from the air, especially under high temperature and humidity, leading to caking or stickiness. Thermosensitive materials risk melting or softening and therefore require careful control of inlet air temperature and dew point (Geldart et al., 2006).

2.4.2 Flowability and System Selection

Flowability determines whether a powder will move easily through hoppers, feeders and conveying lines.

In pneumatic conveying, the Geldart classification is especially useful. As illustrated in Figure 2.5, it maps particle diameter against density to classify powders into Groups A, B, C and D. Geldart (1973) showed that Group A materials fluidize easily, making them ideal for dilute phase. Group B includes free-flowing grains like sugar or sand. Group C includes highly cohesive particles, which resist fluidization. Group D consists of large, dense particles that fluidize poorly but may be conveyed using high-velocity or mechanical systems.

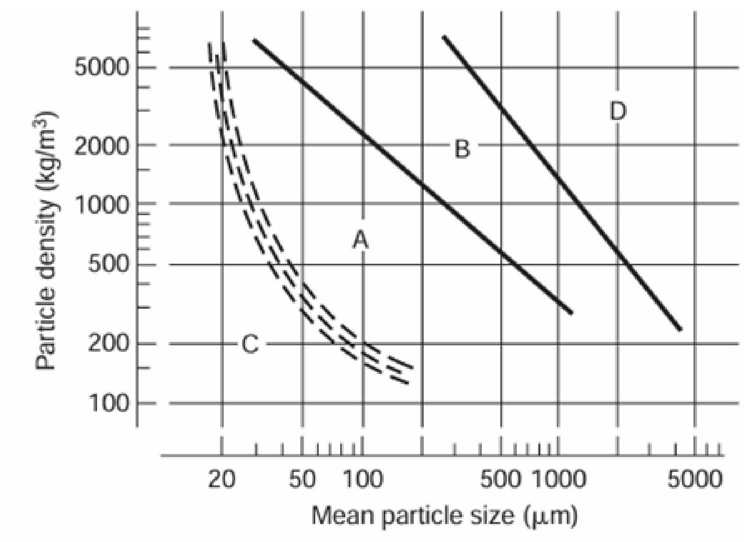

Figure 2.5: Geldart's classification of fluidization behaviour (Geldart, 1973).

This approach provides a valuable starting point for determining whether a material should be conveyed in dilute or dense phase and what fluidization aids might be necessary.

2.4.3 Conveying Velocity Considerations

The selection of conveying air velocity is one of the most critical design decisions. It must be high enough to suspend and move the particles, but not so high as to cause degradation, excessive wear, or energy waste. Table 2.2 contains the typical velocity ranges for both types of conveyng modes. These values must exceed the saltation velocity, defined as the point where particles begin to fall out of suspension. In contrast, dense phase systems must remain below the choking velocity - the upper threshold beyond which pressure loss increases dramatically and flow may become unstable. (Klinzing et al., 2010).

Table 2.2: Typical conveying velocities for different pneumatic conveying modes

Conveying Mode	**Typical Velocity Range (m/s)**
Dilute Phase	15–30
Dense Phase	2-8

Air velocity is also the main contributor to particle degradation. As Scheibel (2018) shows, higher velocities increase kinetic energy, which in turn increases collision intensity with pipe bends and other particles. This causes product attrition and fines formation, reducing product quality and potentially blocking filters.

2.5 Main Components of a Pneumatic Conveying System

Pneumatic conveying systems consist of several integrated components that work together to transport bulk solids through pipelines using a gas stream, typically air. The primary components include air movers (which generate the necessary pressure differential), feeding devices (which introduce material into the system), pipelines and bends (which carry the product to its destination) and gas-solid separation devices (which separate the conveyed material from the gas). The selection, sizing and configuration of each component must consider material properties, process conditions and operational goals to ensure optimal performance and minimal degradation.

2.5.1 Air Movers

Air movers are the driving force behind pneumatic conveying systems, supplying the airflow necessary to transport solids through the pipeline. Their selection is based on the required conveying pressure, air volume and mode of operation (pressure or vacuum). The performance of an air mover has a direct impact on energy efficiency, product integrity and system reliability. The most common are fans, compressors, blowers and vacuum pumps (Mills, 2016).

Fans are low-pressure devices that use rotating blades to move large volumes of air. They operate by imparting kinetic energy to the air, which is then converted to static pressure. According to Werther (1987), fans are typically suitable for applications where pressure requirements are low, such as dust collection or ventilation systems.

Compressors function by significantly reducing air volume to increase pressure and can operate using reciprocating pistons, rotary screws, or centrifugal impellers. As explained by Rhodes (2008), these machines can reach discharge high pressures , making them suitable for long conveying distances or high-resistance systems. A practical concern with compressors is the increase in air temperature resulting from compression, which can affect the stability of heat-sensitive products, potentially causing degradation or microbial growth (Mills, 2016).

As noted by Barber (1997), blowers deliver a fixed volume of air per revolution and build pressure through resistance imposed by the downstream system. They are widely used in dilute-phase pneumatic conveying systems due to their mechanical simplicity, reliability and suitability for continuous operation. However, as the air is compressed and pushed through the system, its temperature increases significantly. This rise in temperature can be problematic for heat-sensitive. Proper management of inlet conditions and temperature rise across the blower is essential to ensure stable conveying and prevent material degradation.

Vacuum pumps generate a pressure differential by reducing the pressure at the receiving end of the conveying line, which causes ambient air to push material through the pipeline. One common mechanism is the rotary vane pump, where vanes slide within a rotor to reduce volume and compress air as it rotates. These systems are effective in maintaining smooth airflow and minimizing pulsation during transport (Barber, 1997).

2.5.2 Feeding Devices

Feeding devices are responsible for introducing solids into the conveying pipeline in a controlled and uniform manner, while also maintaining pressure separation between the upstream storage vessel and the pressurized conveying line. They are a critical interface between the product hopper and the pneumatic flow and their design affects both conveying efficiency and material degradation (Mills, 2016).

Among the available technologies, rotary valves are the most commonly used feeders in dilute phase conveying. They consist of a rotating rotor with several pockets or vanes, which trap product from the upper inlet and discharge it into the pipeline as the rotor turns. This mechanism ensures steady mass flow and pressure isolation between the upstream and downstream sections of the system. Two main configurations are typically used: the drop-through valve, where the product simply falls through the housing due to gravity (Figure 2.6a) and the blow-through valve, where the conveying air flows directly through the rotor pockets as they discharge (Figure 2.6b). The blow-through configuration reduces dead zones and is more compact, making it suitable for hygienic applications and limited-space installations. It also improves the discharge of cohesive or sticky powders by utilizing the conveying air to help empty the rotor pockets (Mills et al., 2004).

The efficiency of a rotary valve is often evaluated in terms of its pocket filling ratio, which depends on rotor speed, particle size, flowability and pressure differential across the valve.

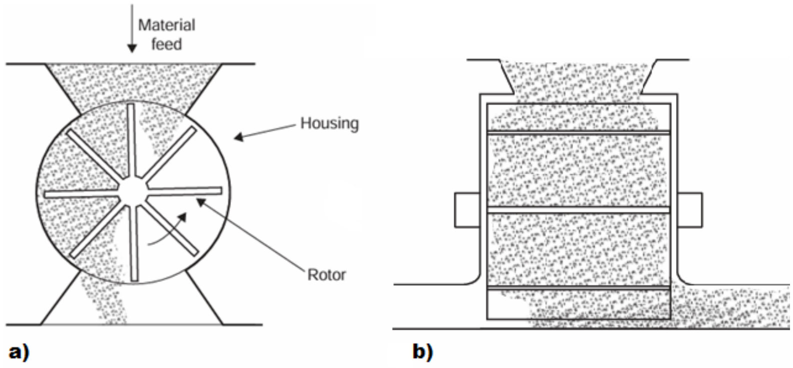

Figure 2.6: Examples of rotary valve configurations: (a) drop-through valve (frontal view); (b) blow-through valve (side view) (Mills, 2016) (Modified).

2.5.3 Pipelines and Bends

Pipelines provide the physical pathway for conveying solids and must be designed to minimize energy losses, product degradation and maintenance requirements. Their layout typically includes both horizontal and vertical segments, which can impact flow behavior depending on the conveyed material and air velocity. According to Mills (2016), the internal diameter of the pipe strongly influences air velocity and pressure drop and must be selected based on the desired conveying regime. The pipe material is equally important: stainless steel is widely used in the food industry due to its corrosion resistance and ease of cleaning (Rhodes, 2008).

Pipeline bends are often necessary due to spatial constraints in industrial layouts, but they are one of the main sources of problems in pneumatic systems. As Solt (2001) describes, bends introduce significant flow disturbances, causing particles to collide with pipe walls and creating localized turbulence, which together contribute to pressure loss and increased product attrition. The geometry of the bend - particularly its radius - has a direct impact on performance. Long-radius bends reduce the intensity of particle impact and are generally preferred for fragile or abrasive materials, according to Klinzing et al. (2010). As particles pass through a bend, their velocity is disrupted by the change in direction. Once they exit, they must be re-accelerated by the air stream in the following straight section. This re-acceleration process requires additional energy and is responsible for a significant pressure loss. Figure 2.7 illustrates this mechanism, showing that the overall pressure drop is composed not only of the loss in the bend itself, but also of the downstream re-acceleration zone (Mills, 2016).

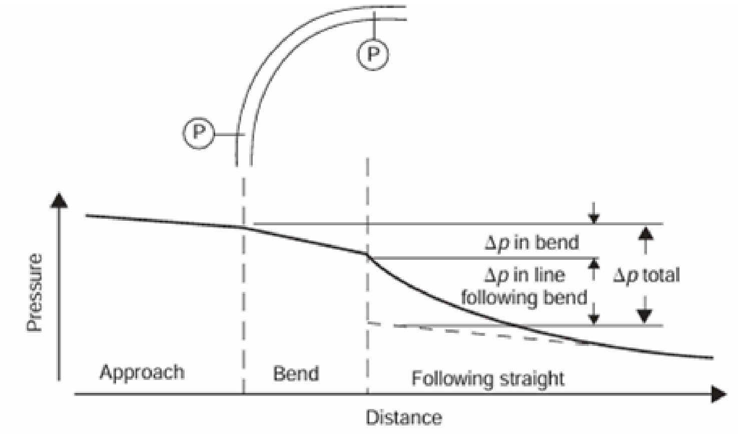

Figure 2.7: Pressure drop elements bends in a pipeline (Mills, 2016).

Minimizing the number of bends and selecting appropriate bend geometry are essential strategies to reduce system resistance and product damage. In addition to pressure losses, bends can also promote powder build-up and increase the risk of segregation, particularly in mixtures with varied particle sizes. For these reasons, bends should be carefully positioned and, where necessary, designed with inspection and cleaning access points (Werther, 1987).

2.5.4 Separation Devices

Gas–solid separation plays a vital role in pneumatic conveying systems, ensuring efficient material recovery while protecting downstream equipment and reducing airborne emissions. The two most commonly employed devices for this purpose are gravity settling chambers and cyclone separators, which differ in their operating principles and efficiency profiles.

Gravity settling chambers function by reducing the velocity of the conveying air, allowing solid particles to separate due to gravitational forces. They are structurally simple and economically attractive, particularly when dealing with larger or denser particles. However, their effectiveness decreases with finer powders or when handling high flow rates (Cruz, 2017).

Cyclone separators, by contrast, exploit centrifugal force by introducing the particle-laden air tangentially into a cylindrical body. The resulting vortex causes particles to spiral along the walls, where they lose kinetic energy and drop into a collection area. This mechanism, as explained by Mills (2016), provides reliable efficiency for a wide range of particle sizes without the need for filters or moving components. The geometry of the cyclone, including its diameter, cone angle and vortex finder, strongly influences both separation efficiency and pressure drop (Couper et al., 2005).

Although cyclones are generally effective and require minimal maintenance, their performance can fluctuate with variations in particle load or flow conditions. As highlighted by Gomide (1983), this variability can lead to particle re-entrainment or increased emissions, especially when dealing with fine or cohesive powders.

Chapter 3

Problem Description

Nestlé's factory in Avanca is an industrial unit of high operational complexity, responsible for the production of various food products. With over a century of operation, it integrates production lines with different levels of technological advancement, which implies the coexistence of modern equipment alongside others that are technologically outdated. This reality, although common in older industrial units, poses a constant challenge in maintaining process performance, safety and quality. In line with the culture of continuous improvement and the high standards that characterize Nestlé, the factory has systematically sought to modernize its systems, reduce operational costs, optimize operational ergonomics and reinforce food and environmental safety standards. Operational excellence is thus one of the key pillars justifying interventions in process segments that no longer efficiently meet the current production requirements.

Within this pursuit of operational excellence, it also became necessary to ensure legal compliance in matters of industrial safety, particularly regarding the prevention of explosions in potentially hazardous atmospheres. The European Union's legal framework in this area is based on two key directives. The Directive 1999/92/EC establishes the minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres. Meanwhile, Directive 2014/34/EU regulates the design and marketing requirements of equipment and protective systems intended for use in such environments.

These directives have been transposed into Portuguese national law through two distinct legislative decrees:

- Decreto-Lei No. 236/2003, which transposes Directive 1999/92/EC and establishes employer obligations concerning risk assessment, zone classification and implementation of preventive measures;

- Decreto-Lei No. 111-C/2017, which transposes Directive 2014/34/EU and defines the technical and certification requirements for equipment intended for explosive risk zones.

Although these decrees set out the mandatory legal framework, their practical technical application is supported by harmonized standards officially recognized by the European Commission. In the context of explosion prevention in industrial atmospheres, three key standards stand out:

- EN 1127-1, which defines principles for ignition prevention and enumerates potential ignition sources;
- EN 60079-10-1, which deals with the classification of zones with the presence of flammable gases or vapors;
- EN 60079-10-2, which addresses the classification of zones at risk due to the presence of combustible dusts.

Adopting these technical standards is highly recommended, as it ensures the so-called *presumption of conformity* with the legal requirements of the ATEX directives and respective national decrees. Thus, the directives provide the legal framework, the Decree-Laws establish national obligations and the EN standards offer the technical criteria to ensure that implemented solutions comply with legal and industrial safety requirements.

In this context, Nestlé's Avanca factory contracted an external specialized company to carry out a systematic assessment of explosion risks within its facilities. This assessment resulted in the development of an Explosion Protection Document, containing the classification of hazardous zones, analysis of ignition sources and proposed prevention and protection measures, all defined based on the referenced technical standards.

According to the level of risk resulting from the assessment, the prevention and protection measures were categorized by priority level:

- "must": measures that must be adopted to ensure full compliance with legislation;
- "recommended": additional measures to improve the level of safety;
- "not to forget": measures currently implemented on site that must continue to be maintained over time.

This project focuses on providing technical support to the powdered milk sector, where a "must" risk was identified in the fan responsible for conveying the product to the agglomeration tower. This equipment, had signs of wear and did not fully comply with ATEX certification requirements and was classified as a high-priority intervention target. The analysis determined that the interior of the fan and the powder conveying duct are continuous-grade release sources, with their internal volumes classified as Zone 20. Additionally, areas within one meter around joints, flexible connections and inspection doors were classified as Zone 22. As such, it was recommended to replace the fan by a certified air mover, ensuring legal compliance and process integrity.

In ATEX classification, Zone 20 refers to areas where an explosive atmosphere in the form of a combustible dust cloud is present continuously or for long periods. Zone 21 covers areas where such an atmosphere is likely to occur occasionally during normal operation. Zone 22, in turn, refers to areas where an explosive dust atmosphere is not likely to occur in normal operation, but if it does, it will only persist for a short duration. Proper identification of these zones is crucial for ensuring that all installed equipment meets the required safety standards and minimizes the risk of ignition.

This situation created the need to redesign the pneumatic conveying system in this section of the product flow. Furthermore, the direct contact between the powder and the rotating fan blades had the associated risk of ignition. In addition to the identified risk, the fan was already obsolete, presenting failures in operational performance (i.e., not meeting the expected conveying rate) and not adhering to best hygienic design practices.

3.1 Understanding the Production Process

Before delving into the identified problem and the proposed solution, it is essential to contextualize the sector in which the project is embedded. The process carried out in this sector aims to modify the properties of powdered milk, making it more suitable for specific applications - in this case, instant preparation in vending machines. The production chain encompasses several technological stages, from the reception and mixing of raw materials, to final product packaging. Figure 3.1 illustrates the main phases of the process:

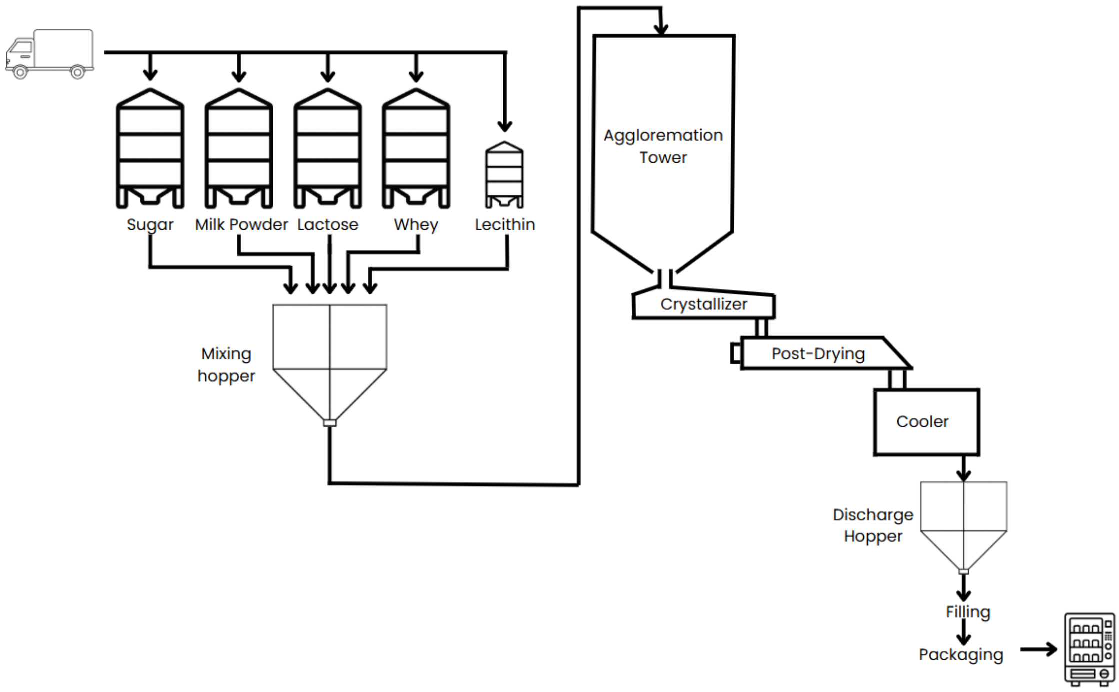

Figure 3.1: Diagram of the overall process.

3.1.1 Raw Materials and Mixing

The raw materials used - powdered milk, whey, lactose, lecithin and sugar - are individually stored in silos. The final formulation depends on the specific recipe, with quantities precisely dosed, weighed and homogenized in mixing equipment. This mixture forms the base of the product and is subsequently transferred to the agglomeration tower.

3.1.2 Agglomeration

At the inlet of the agglomeration tower, the dry powder comes into contact with sprayed water, which promotes surface moistening of the particles. This moisture induces the adhesion of fine particles, promoting the formation of agglomerates with physicochemical properties suitable for instant use.

3.1.3 Crystallization

After agglomeration, the powder still retains residual moisture and certain soluble components may not be fully crystallized. The crystallization stage exposes the product to controlled temperature and time conditions, allowing the formation of stable crystals. This process contributes to improved flowability, physical stability and shelf life of the product.

3.1.4 Post-Drying

Although the agglomeration process ensures partial drying, additional drying is required to reduce residual moisture to safe levels. This stage, carried out with hot air at moderate temperatures, aims to achieve a final moisture content that ensures microbiological stability and prevents undesirable physicochemical reactions during storage.

3.1.5 Cooling

Once drying is completed, the powder remains at a high temperature. Before being directed to the filling line, it undergoes a cooling process, which prevents condensation upon contact with packaging materials and avoids thermal alterations that could compromise the sensory and nutritional quality of the product.

3.1.6 Filling and Packaging

In the final stage, the product is packed into specific containers that protect it against environmental factors such as humidity, oxygen, light and potential contaminants. Packaging ensures not only the preservation of the powdered milk's properties but also convenience and safety for the end consumer.

3.2 Location, Condition and Critical Analysis of the Current System

The problem identified previously occurs at a very specific stage of the production process: the transport of the already homogenized powder mixture from the end of the mixing stage to the inlet of the agglomeration tower, as shown in Figure 3.2.

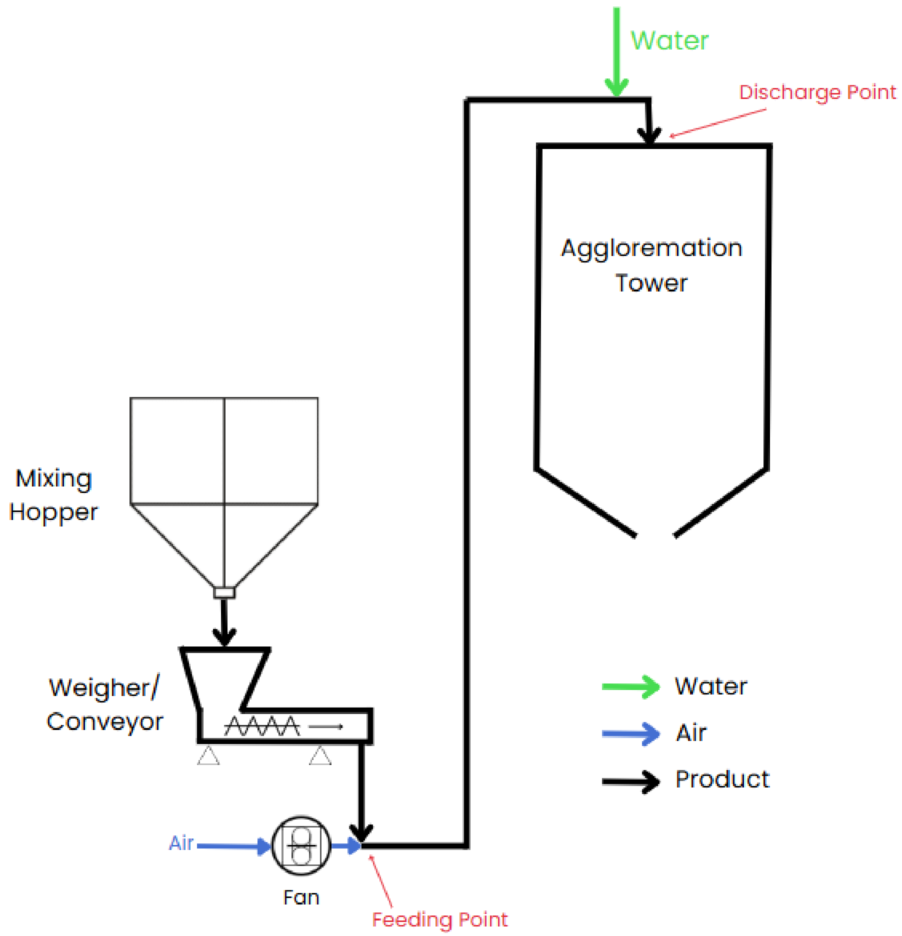

Figure 3.2: Diagram of the specific process section.

In the current installation, transport is carried out by a positive pressure pneumatic conveying system, composed of a centrifugal fan and a stainless steel pipeline with a diameter of 125 mm. The fan is installed immediately after the weighing conveyor, which serves as the product feeding point. The product is propelled through approximately 13 meters of horizontal piping, with a vertical rise of about 17 meters and 5 bends, up to the top of the agglomeration tower. Figure 3.3 helps to visualize the current system.

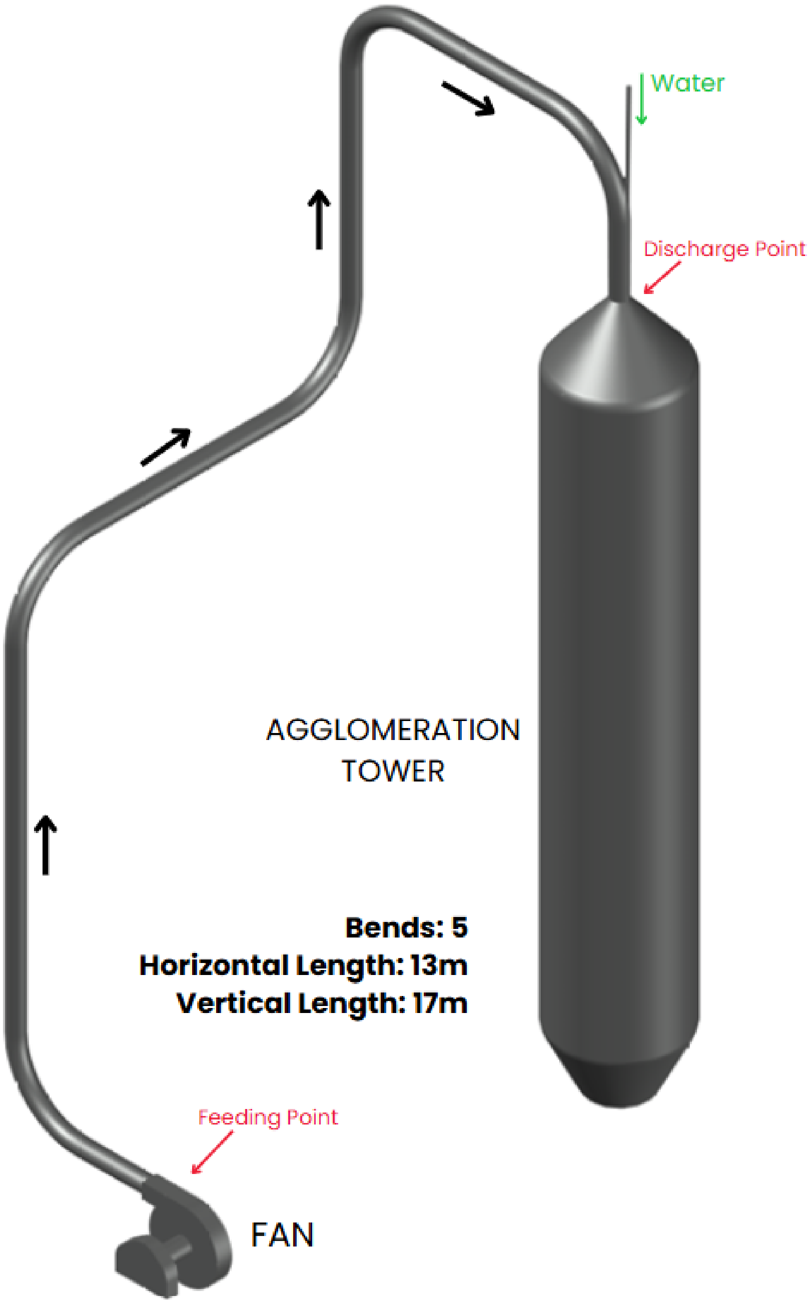

Figure 3.3: Isometric drawing of the current conveying system

The correct operation of this system is essential to ensure stable feeding to the tower and, consequently, the efficiency and continuity of the subsequent process. Any interruption, instability, or limitation at this stage has a direct impact on the production capacity of the sector and the quality parameters of the final product. The technical analysis of this system revealed several limitations that, when considered together, justify the need to redesign the current solution:

- **Insufficient capacity:** the fan has a maximum conveying capacity of approximately 1300 kg/h, which is lower than the capacity of the upstream weighing conveyor (2000 kg/h). This discrepancy results in under utilization of the existing equipment and directly limits the production line throughput;

- **Lack of feeding control:** the absence of a dedicated rotary valve at the system inlet prevents precise control of dosing and sealing between air and product. This limitation contributes to undesirable variations in product flow and reduces predictability in dilute phase conveying;
- **Safety and legal compliance:** the fan operates in a classified Zone 20 area without ATEX certification. Furthermore, physical signs of wear and friction marks were detected on its interior, representing a risk of ignition due to mechanical contact.

These limitations, when analyzed collectively, reveal an outdated system with deficiencies in performance, safety and legal compliance, reinforcing the urgency of implementing a more efficient, safer and production-adapted technical solution.

Chapter 4

Solution

4.1 Design Criteria and Constraints

The redesign of the pneumatic conveying system should be guided by a set of predefined criteria, derived both from the limitations observed in the current system and from the requirements of the production process. These criteria should be the basis for selecting the appropriate technology, pre-dimensioning the equipment and preparing a *URS – User Requirement Specification*. An *URS* is a structured technical document developed internally by Nestlé to formalize all necessary requirements for the design and acquisition of new equipment or systems. Its main function is to serve as a communication platform between the project team and suppliers, ensuring that the proposals received are aligned with the factory's operational, technical and regulatory objectives.

One of the main requirements identified is the need to increase the conveying capacity from 1300 kg/h to 2000 kg/h, which corresponds to the upper limit of the existing weighing conveyor. This improvement aims to eliminate the bottleneck caused by the current fan and ensure a stable product flow to the agglomeration tower.

Another key criterion is the retention of the existing piping. The stainless steel conveying line, approximately 13 meters in horizontal length, with a vertical elevation of 17 meters and 5 bends, had to be reused in the proposed solution. This decision is intended to minimize physical modifications to the installation and reduce implementation costs. As such, the new equipment must be compatible with the geometric and hydraulic characteristics of the current piping (internal diameter of 125 mm).

Additionally, the new solution must ensure compliance with ATEX requirements, integration with upstream and downstream equipment, without compromising the operational logic of the production line and compatibility with Nestlé's internal requirements, particularly in terms of hygienic design, operational safety, ergonomics and ease of operation.

4.2 Technology Selection

Defining the technical architecture of the new pneumatic conveying system required a comparative analysis of the main available configurations, based on factors such as the nature of the product, process requirements, installation geometry and applicable legal requirements.

The decision involved two fundamental choices: the mode of product transport (dilute/lean phase vs dense phase) and the mode of air movement (positive pressure vs negative pressure).

4.2.1 Dilute/Lean Phase vs. Dense Phase

The current system already operates in lean phase, despite being undersized. This background proved to be an important factor in itself, as it demonstrates the process's compatibility with this configuration and internal experience in its operation and maintenance.

Nevertheless, a critical reassessment was conducted, taking into account the alternatives. Dense phase conveying, although effective in certain contexts, was ruled out for several reasons:

- The injection of water into the powder, which occurs immediately before the agglomeration tower, requires a continuous and homogeneous product flow. If transport were performed in pulses (as in dense phase), the mixture of powder and water would become unstable, impairing product quality and process efficiency;
- Dilute phase allows for a more predictable flow, minimizing the risk of variations in moisture and product density at the tower inlet.

From a materials handling perspective, the milk powder in question belongs to Geldart Group A, which includes aeratable powders with small particle sizes and low cohesive forces. In this case, the powder has a mean particle size of approximately 100–200 μm and a bulk density in the range of 500–750 kg/m^3, characteristics that further confirm its classification within this group. These materials exhibit good fluidization behavior and are particularly well-suited for dilute phase pneumatic conveying, where they can be suspended and transported efficiently without major issues such as plugging or excessive degradation.

Moreover, dilute phase conveying is the most widely used method in the food and dairy industry due to its ability to support continuous processing requirements. Its operational predictability and ease of integration with hygienic design practices make it a preferred choice, especially when handling free-flowing, non-abrasive powders like milk powder.

4.2.2 Positive Pressure vs Negative Pressure

The second aspect analyzed was the method of air movement. Although vacuum systems offer advantages in terms of dust containment and environmental control, their application was considered unsuitable in this case due to several process, layout and operational constraints:

- The agglomeration tower is open at the bottom, with powder falling directly by gravity. This setup does not allow for effective suction. Additionally, the available space in the area is severely limited, making it difficult to integrate a vacuum pump or separation equipment without significant structural changes;
- Vacuum systems also tend to entrain fine particles. Although filtration units are standard, the high dust load expected in this application could result in greater product losses and more frequent maintenance interventions - undesirable in a process handling milk powder, which is sensitive to fines;
- From an operational standpoint, vacuum systems are not commonly used in the factory. In contrast, the technicians have extensive experience with positive systems, which translates to more reliable maintenance, easier troubleshooting and safer long-term operation.

Positive pressure conveying offers several advantages in this context, as it ensures stable and continuous product flow into the agglomeration tower and aligns with existing factory standards and available technical expertise.

Given these considerations, the selected configuration is a lean-phase pneumatic conveying system operating under positive pressure. The product will be introduced into the conveying line through a rotary valve, which ensures consistent feeding and proper system sealing. This valve will be ATEX-certified and suitable for installation in Zone 20, as it is the point where the product passes through, making it a potential source of explosive dust atmosphere. The air mover will be positioned more than one meter away from the rotary valve, and consequently, ATEX certification will not be required for it, thereby resolving the ATEX non-compliance issue.

Since the system operates under positive pressure, the possible types of air mover are limited to compressors, blowers, or fans. However, as previously discussed, fans are not suitable in this context due to the unacceptable contact between the powder and the rotating blades, which presents a risk of ignition. Therefore, based on the calculated pressure drop, the final choice will be between a blower and a compressor, with preference given to the option that meets the system's pressure and flow requirements more efficiently.

4.3 User Requirement Specification

With the technology selected, the URS elaboration was needed. The main advantages associated with the development of this document include:

- Standardization and compatibility with existing equipment: clearly defined technical requirements allow the new system to utilize models and spare parts already available in the factory, thus reducing costs associated with spare parts storage;
- Ease of intervention and leverage of existing know-how: maintaining uniformity in equipment allows the use of existing technical knowledge within the operations and maintenance teams, facilitating future interventions;

- Integration of safety, health, environmental and hygienic design requirements: the specification can mandate the inclusion of specific features in the equipment. Additionally, it ensures compliance with hygienic design criteria (elimination of dead spaces, sloped surfaces, absence of open belts, proper anchoring of equipment feet, among others);
- Agility in technical validation: the pre-definition of acceptance criteria facilitates the FAT (Factory Acceptance Test) and SAT (Site Acceptance Test), making the validation process more transparent and aligned with company expectations.

In this way, the URS not only guides the supplier in developing the most suitable solution but also protects the company's long-term interests, promoting operational efficiency and safety. In the specific case of this project, the URS refers to the installation of a new lean phase pneumatic conveying line between the outlet of the weighing conveyor and the inlet of the agglomeration tower. As the project manager, the work involved a comprehensive approach to gathering requirements and integrating information across multiple technical disciplines within the factory. This process began with organizing and leading meetings with specialists from diverse departments, including Quality, Safety, Maintenance, Production and Automation, to ensure a holistic understanding of the project needs. Additionally, an extensive review of existing technical documentation - such as data sheets, internal standards and factory layouts - was conducted to establish a solid knowledge base. A detailed on-site survey was carried out to examine interfaces and spatial constraints firsthand, facilitating accurate assessment of the physical environment. Complementing these activities, an independent technical study was undertaken to deepen understanding of the fundamental principles governing each domain involved, ensuring that all aspects of the project were considered with the necessary rigor and expertise.

This process ensured that all technical requirements were properly substantiated, aligned with the factory's operational and strategic objectives and presented in a complete and comprehensible format for potential suppliers. The URS was developed following Nestlé's internal standardized model. The following sections of this chapter explain the structure of the URS, the purpose of each module, the specific information included and how this information was gathered. Some confidential data, including detailed product formulations and exact physical properties, could not be disclosed. In such cases, representative ranges were provided instead, ensuring that the document remains functional and technically valid without compromising sensitive information.

The first two pages of the document include general administrative content: the General Information on URS (such as author, contact person, version and document status), General Project Information (identifying the site and local responsible), a section for company approvals (with designated signatories) and the Table of Contents, which outlines the modular structure of the document. The next sections of this chapter will walk through each of the URS modules.

4.3.1 Purpose and Scope

The first section of the URS defines the overall objective of the project and sets the boundaries for the supplier's responsibilities. It introduces the installation of a new lean-phase pneumatic conveying line, operating under positive pressure.

This module clarifies the scope of supply, listing the equipment and services expected to be provided by the supplier, as well as identifying components or systems that are explicitly excluded from the scope. Additionally, it establishes a formal protocol for deviations: any proposed variation from the requirements must be submitted in writing by the supplier and requires written approval from Nestlé's designated project contact. This guarantees consistency with internal engineering standards and supports proper traceability of decisions throughout the project lifecycle.

This section also includes a schematic representation of the system layout, which serves to illustrate the general architecture of the conveying line, the product and air streams and the main equipment interfaces. Although detailed descriptions are avoided at this stage, the visual overview helps contextualize the project and serves as a reference for the following sections of the document.

In summary, the Purpose & Scope section plays a crucial role in establishing the framework for the project, ensuring that all parties share a common understanding of the objectives, deliverables and limitations associated with the conveying system.

4.3.2 Product and Process Parameters

This section outlines the main physical and process-related characteristics of the materials to be handled by the pneumatic conveying system. These parameters are essential for the correct design and sizing of the equipment. In a complete version of the document, each product would be individually identified with its official designation and associated technical data. However, this simplified version uses general descriptors to preserve confidentiality while maintaining the document's functional value for technical analysis.

Typically, the URS would include a dedicated column for each product, specifying individual properties but in this version, the data is consolidated and presented as ranges, which reflect the expected variability among the powder type. These values were provided by the Production department, based on validated technical datasheets and historical records.

Table 4.1 summarizes the key process parameters considered during the system's pre-dimensioning:

Table 4.1: Simplified physical parameters of milk powder stream

Property	**Range**
Bulk Density [kg/m³]	500 – 750
Particle Size Range [µm]	100 – 200
Temperature [°C]	36 – 38

These values ensure that the conveying system can accommodate all product variants without compromising performance.

4.3.3 Installation Environment

The Installation Environment section outlines the physical, hygienic and infrastructural conditions that must be considered in the design and specification of the pneumatic conveying system. The equipment is to be installed in a high-hygienic zone, where only dry cleaning procedures are permitted due to the nature of the surrounding process and to avoid moisture-related contamination risks. The detailed internal hygienic design standards applicable to this area are provided separately as an attachment to the URS and suppliers are expected to comply fully with it.

This section also includes the installation layout and describes relevant spatial constraints to ensure integration with the existing production environment. It further defines the type of floor and its suitability for mechanical installation, as well as the requirement for suppliers to declare the catastrophic load of their equipment. The system is to be installed indoors, in a climate-controlled environment where the air is pre-conditioned by an existing Air Handling Unit (AHU) to ensure consistent temperature and humidity levels. No additional air dehumidifier is included within the scope of the conveying system. The environmental conditions of the installation area are summarized in Table 4.2.

Table 4.2: Environmental conditions of the installation area

Parameter	**Minimum**	**Maximum**
Temperature [°C]	20	35
Relative Humidity [%RH]	35	55

Regarding utilities, the electrical supply requirements are summarized below and must be respected to ensure compatibility with the site's power infrastructure, as shown in Table 4.3.

Table 4.3: Electrical utility requirements

Utility	**Specification**
Supply Voltage	400–420 V
Frequency	50 Hz
Max Power Consumption	up to 30 kW

These environmental and infrastructural constraints were validated through layout analysis, technical meetings and on-site surveys, ensuring that all proposed equipment is suitable for the conditions present in the intended installation zone.

4.3.4 Upstream and Downstream Machinery

Before entering the conveying pipeline, the product and conveying air are prepared and introduced by several upstream components that must be carefully considered during system integration.

In this case, the conveying air is supplied from an existing AHU, which delivers filtered air within the required process conditions. The system also includes a new airmover, along with process instrumentation such as a pressure sensor, temperature sensor and a rotary valve with a feeding hopper. These elements ensure stable airflow, monitoring capability and controlled product feeding into the pneumatic line. To facilitate integration, the URS presents a table that indicates whether each component is existing or newly supplied, whether it falls within the scope of the current project and the type of signal interfaces involved.

In addition, one key process constraint is highlighted: the temperature of the conveying air at the feeding point must remain between 30°C and 50°C, in order to ensure compatibility with the conveyed product and maintain overall system performance. The same tabular structure and logic are applied in the subsequent section to describe the equipment located downstream of the system. This structured presentation ensures clarity for suppliers and guarantees that all upstream interfaces are properly accounted for in the design and implementation phases.

4.3.5 Machinery Specifications

The machinery selected for the conveying line must be capable of ensuring a continuous and stable product flow of 2000 kg/h, under the conditions specified in the previous sections. This capacity was used as a reference throughout the pre-dimensioning process and was defined based on production demand and upstream system capability. The main components required for the conveying system are described in detail in this section, which outlines the technical specifications and design expectations for each item.

The air mover is one of the critical elements, responsible for generating the airflow necessary to convey the milk powder through the pipeline. The preferred suppliers listed in the URS are Aerzen, Pedro Gil and Atlas Copco, as these manufacturers are already validated within the factory and offer reliable service. The air mover must include a Variable Frequency Drive (VFD) to allow flexible control of the air velocity, enabling the system to adapt to changes in flow rate or process conditions without compromising efficiency or product quality.

The air pipeline connects the air mover to the feeding point and is AISI 304 stainless steel, equipped with all necessary couplings and fixations. It also includes a pressure sensor, which serves as a safeguard to detect potential blockages or flow instability in the line and a temperature sensor.

For the product feed system, the milk powder is introduced into the air stream using a rotary valve mounted beneath a feeding hopper. The supplier specified for this component is DMN Westing House, a standard partner of Nestlé for pneumatic conveying applications. This choice reflects the factory's preference for equipment with proven hygienic design, high reliability and full compliance with ATEX requirements for fine powders.

The conveying pipeline itself is an existing line reused for this project, with characteristics and constraints already discussed in earlier chapters. It has an internal diameter of 125 mm, includes 5 long-radius bends, 17 meters of vertical length and 13 meters of horizontal length. All product-contact parts are made from AISI 304 stainless steel. The chosen flange connection type is the Milk Thread (DIN 11851), which is widely used in the dairy industry for its hygienic sealing, ease of cleaning and compatibility with the factory's installed base.

The URS also requests that suppliers propose an appropriate service and maintenance plan, considering the operational profile of the system. The goal is to ensure availability of support during commissioning and to define a preventive maintenance strategy.

Finally, this section outlines the structure of the quotation, specifying how costs, technical data and documentation must be itemized. This ensures consistency across supplier proposals and facilitates a transparent technical and economic evaluation.

4.3.6 Safety, Health and Environment (SHE)

The conveying system must comply with Nestlé's safety and environmental standards, particularly those related to ATEX zones. The interior of the pipeline and rotary valve is classified as Zone 20, while the surrounding area is Zone 22. All components must be certified for use in these atmosphere and motors must include local lockable isolators with PLC feedback where applicable.

4.3.7 Cleaning and Hygienic Design

The conveying system must be compatible with the hygiene level required for its installation area. Only dry cleaning procedures are permitted in this environment during normal operation. In specific cases, off-site wet cleaning may be required for certain sections of the pipeline where product deposits cannot be fully removed by dry methods. All hygienic design criteria - including materials and construction standards - are detailed in Nestlé's internal specifications, which are provided as an attachment to the URS.

4.3.8 General Design Requirements

The system must be built using components that are compatible with the existing infrastructure and operational practices of the factory. Where possible, previously validated suppliers and models should be used to ensure reliability, ease of integration and availability of spare parts.

Specific material requirements apply, such as the use of EPDM O-rings and H1 food-grade lubricants, to comply with food safety and hygienic design criteria. All components must be suitable for continuous industrial operation and allow for straightforward maintenance and cleaning.

If alternative components are proposed, they must be technically equivalent and subject to prior approval. This ensures overall consistency, safety and long-term performance of the installation.

4.3.9 Quality and Performance Acceptance Criteria

To ensure that the conveying system meets its operational objectives, a set of functional and performance criteria has been defined for acceptance. These criteria are verified during two key stages of equipment validation: Factory Acceptance Test (FAT) and Site Acceptance Test (SAT).

On one hand, FAT is performed at the supplier's site before shipment, under controlled conditions. It verifies conformity with the technical specification and ensures basic functionality.

On the other hand, SAT is conducted at the factory after installation and integration. It validates performance under real operating conditions and confirms the system's readiness for production.

The main functional requirement is that the system must sustain a transport capacity of 2000 kg/h under normal process conditions. Additionally, the following operational performance indicators, compiled in Table 4.4 must be met at Final Acceptance, defined as three months after commissioning.

Table 4.4: Operational performance criteria at Final Acceptance

Parameter	**Units**	**Minimum**	**Maximum**
Expected Continuous Run Time	h	24	216
Inspection Time	min	–	5
Inspection Frequency	1 per X	18h	–
Lubrication Time	min	–	5
Lubrication Frequency	1 per X	week	–
Change-over Time*	min	10	40
Unplanned Stoppages	%	–	5
Unplanned Stoppages + Speed Loss + Waste/Rework	%	–	7

* *Depending on cleaning and validation needs.*

These parameters were defined in collaboration with the production and maintenance teams, aiming for a balance between performance expectations and operational feasibility. While the system is expected to perform reliably, the values acknowledge routine interruptions for inspection, cleaning and minor adjustments - ensuring that performance targets are demanding yet realistic.

4.3.10 Electrical and Automation

The integration of the conveying system with the factory's electrical and automation infrastructure is a key element for operational reliability, safety and traceability. This section defines the requirements that ensure the proper installation, communication and control of the equipment within the existing industrial network.

To ensure adequate protection of electrical components, Ingress Protection (IP) ratings are specified, which classify the degree of sealing against dust and water. These ratings are essential for selecting devices suitable for each installation area. In this project, components exposed to airborne powder or located near cleaning operations must meet at least IP65, ensuring total dust-tightness and protection against water jets. However, not all components require the same IP rating. Each is specified individually according to its installation environment and function. Protected cabinets or components in control rooms may be rated lower (IP54), while sensors or actuators near the conveying line may require higher ratings (IP66), depending on exposure.

For automation, the system must be managed by a Programmable Logic Controller (PLC). PLCs are responsible for real-time control and monitoring, receiving signals from sensors and executing logic to control equipments. In line with factory standards, the selected PLC must be from Allen Bradley, ensuring full compatibility with existing infrastructure and ease of integration with Nestlé's maintenance and support protocols.

Communication between the PLC and other system components must be established via Ethernet/IP - an industrial protocol that provides real-time data exchange and supports integration with the factory's Manufacturing System. This connectivity enables batch tracking, alarm handling and process step confirmation directly from the conveying system.

The interface with operators is defined via a local HMI (Human-Machine Interface). The selected platform must be Wonderware, a software that offers flexible graphical dashboards and intuitive controls. Additionally, the system must connect to a Historian, a specialized database that records time-series data from the process - including pressures, flows, temperatures and alarms - allowing for performance monitoring and troubleshooting,

4.3.11 Installation and Commissioning

The supplier is responsible for the installation and commissioning of all components within the project scope, except where otherwise specified. Activities must be carried out in close coordination with the site's engineering team to ensure proper integration with existing systems.

Electrical installation on site, including cabling and connection to the factory's power and control systems, will be performed by Nestlé. The supplier must provide all required documentation and must be available to support the site team during connection and testing. During mechanical installation, the supplier is expected to supervise the correct positioning of equipment, alignment with utilities and interface preparation. Commissioning activities must include functional checks, control loop optimization and verification of communication with automation systems. The supplier shall also ensure product flow integrity and system stability under real production conditions, supporting initial operations until final validation is achieved.

4.3.12 Training and Documentation

The supplier must provide training to the factory personnel, including operators, maintenance technicians and supervisors. Training sessions must cover system functionality, routine operation, basic troubleshooting and cleaning procedures. All training must be delivered in both Portuguese and English, ensuring accessibility for all personnel involved. Trainers must be proficient in both languages, with a minimum recommended level of C1 in Portuguese and B2 in English.

4.3.13 Attachments

The URS includes a set of attachments that support and complement the requirements described. These attachments provide visual, technical and procedural references to facilitate supplier understanding and proposal alignment. Included in the original version are the installation layout (identifying the available space and equipment positioning), an isometric drawing of the conveying pipeline and a copy of the relevant internal hygienic design standard. Additional specifications or site references may be provided separately during the request for quotation phase, if required.

4.3.14 Publication and Market Consultation

This data were essential for performing the pre-dimensioning analyses presented in following chapters and for supporting decision-making regarding the type of technical solution to be implemented. Once finalized and approved internally, the URS is submitted to Nestlé's procurement team, which publishes it to pre-qualified suppliers. These suppliers analyze the defined technical and commercial requirements and, if interested, submit proposals and respective quotations. Proposals may include a Deviation List, identifying any deviations from the URS and suggesting alternative solutions. It is then the responsibility of the factory's technical team, in coordination with the procurement department, to evaluate the received proposals, clarify doubts with suppliers and select the solution that best fits the project.

4.4 Preliminary Air Mover Design

his section calculates the key design parameters (pressure drop and power) needed to size the blower for the new system. The preliminary design of the pneumatic conveying system was carried out with the aim of estimating the main operating parameters and selecting the appropriate components, based on the product characteristics, the route and the chosen technological configuration. This initial design does not replace the detailed calculations provided by suppliers, but it allows for a technical validation of the proposed solution, ensures the feasibility of reaching the target capacity of 2000 kg/h and supports the preparation of a technically sound URS for submission to the market.

4.4.1 Known Parameters and Assumptions

In order to perform the preliminary calculations for the pneumatic conveying system, a set of known input data and design assumptions was established, summarized at Table 4.5. These parameters serve as the foundation for estimating key process variables, including conveying air velocity, volumetric flow rate, pressure drop and equipment sizing.

The air density and pressure values correspond to free air conditions at sea level, commonly used as reference values in pneumatic conveying design. These are suitable for estimating the required air flow rate and pressure drop under standard conditions. Unless otherwise noted, these values will be maintained throughout the subsequent design calculations.

4.4.2 Pipe Cross-Sectional Area

To calculate the volumetric flow rate of the conveying air, the internal cross-sectional area of the pipe must first be determined. This area is derived from the pipe's internal diameter, according to

Table 4.5: Process and pipeline parameters

Product		**Pipeline configuration**	
Product type:	Milk powder	Internal pipe diameter:	$D = 0.125\,\text{m}$
Mass flow rate:	$\dot{m}_{prod} = 2000\,\text{kg/h}$	Horizontal pipe length:	$L_{horizontal} = 13\,\text{m}$
Average Density:	$\rho_{produ} = 600\,\text{kg/m}^3$	Vertical pipe length:	$L_{vertical} = 17\,\text{m}$
Mean particle diameter:	$d_p = 150\,\mu\text{m}$	Number of 90° bends:	$N_{bends} = 5$
		Bend radius:	$r_b = 1\,\text{m}$
Ambient and physical conditions			
Air temperature:	$T = 20°\text{C}$	Atmospheric pressure:	$P_{atm} = 1.013\,\text{bar}$
Air density:	$\rho_{air} = 1.225\,\text{kg/m}^3$	Gravitational acceleration:	$g = 9.81\,\text{m/s}^2$

the formula for the area of a circle:

$$A = \frac{\pi D^2}{4} \tag{4.1}$$

Where A is the internal cross-sectional area of the pipe $[\text{m}^2]$ and D is the internal diameter of the pipe $[\text{m}]$. The calculated area is:

$$A = \frac{\pi \cdot (0.125)^2}{4} = 0.01227\ \text{m}^2$$

This cross-sectional area will be used in subsequent calculations.

4.4.3 Minimum Conveying Air Velocity

In pneumatic conveying systems, the conveying air velocity is a critical parameter to ensure efficient and reliable operation. If the air velocity is too low, particles may fall out of suspension, leading to pipeline blockages. Conversely, excessively high velocities increase pressure drop, accelerate pipe wear due to erosion, promote particle degradation by impact and result in unnecessary energy consumption. It is important to note that the velocity of the gas phase is not equal to the velocity of the solid particles. Furthermore, particle velocities may vary throughout the pipeline due to gravitational effects, turbulence and differences in particle size or density. The exact determination of the minimum conveying velocity is complex and depends on multiple factors.

According to Mills (2016), empirical design guidelines for dilute-phase pneumatic conveying, the minimum conveying air velocity C_{min} is typically greater than 10 m/s. However, this value must be adjusted with an appropriate safety margin of 20% to account for process variability and uncertainties. For design purposes, the air velocity C_1 is usually taken as:

$$C_1 = C_{min} \cdot (1.2) \tag{4.2}$$

In this study, a conservative value of 22 m/s was adopted as the conveying air velocity for design purposes. This value is consistent with best practices for the dilute-phase transport and reflects a balance between operational safety and energy efficiency.

The adequacy of this design velocity can later be validated through supplier simulations or on-site commissioning data. For the purposes of this preliminary study, it will serve as the basis for calculating the required volumetric and mass air flow rates.

4.4.4 Air Flow Rate Calculation

With the conveying air velocity established at $C_1 = 22\,\text{m/s}$ and the pipe internal cross-sectional area previously calculated as $A = 0.01227\,\text{m}^2$, the volumetric and mass flow rates of air required for the system can now be determined. The Volumetric air flow rate, Q_{air}, is given by:

$$Q_{air} = C_1 \cdot A = 22 \cdot 0.01227 \approx 0.270\,\text{m}^3/\text{s} = 972\,\text{m}^3/\text{h} \tag{4.3}$$

And the air mass flow rate, $\dot{m}_{air}$, using the assumed air density of $\rho_{air} = 1.225\,\text{kg/m}^3$ is:

$$\dot{m}_{air} = \rho_{air} \cdot Q_{air} = 1.225 \cdot 0.270 \approx 0.331\,\text{kg/s} \approx 1192\,\text{kg/h} \tag{4.4}$$

4.4.5 Solids Loading Ratio

The solids loading ratio, ϕ, is defined as the ratio between the mass flow rate of the conveyed product and the mass flow rate of the conveying air and is a valuable indicator for characterizing the nature of the flow in pneumatic conveying systems.

$$\phi = \frac{\dot{m}_{prod}}{\dot{m}_{air}} = \frac{0.556}{0.331} \approx 1.68 \tag{4.5}$$

This value indicates that for each kilogram of air used, approximately 1.68 kilograms of milk powder are conveyed. According to Mills (2016), while solids loading ratios in dilute-phase pneumatic conveying can reach values in the range of 15 under optimal conditions, significantly lower values are expected in systems operating at low pressure or with long conveying distances. In the present case, the system operates under low-pressure conditions and includes a substantial vertical elevation, which naturally limits the achievable solids-to-air ratio. The calculated value is therefore consistent with design expectations and confirms that the system remains well within the dilute-phase conveying regime.

4.4.6 Supply Pressure and Its Role in Air Mover Selection

In the design of pneumatic conveying systems, the air mover must be selected based on two key parameters: the required volumetric air flow rate and the corresponding supply pressure. While the volumetric air flow rate defines the quantity of air that must be delivered per unit of time - previously calculated - the supply pressure indicates the pressure level that the air mover must provide to overcome the resistance of the conveying system.

The supply pressure depends on the total pressure drop that occurs along the conveying line. This pressure drop reflects the overall resistance to flow imposed by the system and is influenced by several design and operating factors, including pipeline length, geometry, air velocity and material characteristics. Determining the supply pressure is therefore essential for selecting an air mover capable of ensuring stable product conveying under the specified conditions.

The total pressure drop is typically evaluated along the conveying line segment between the feeding point - where the solid enters the pipeline - and the final discharge point. This is the portion of the system where the gas-solid mixture is conveyed and where the most significant pressure losses occur due to friction, bends and acceleration.

Although there may be minor pressure losses in the upstream section between the air mover and the feeding point, these are generally negligible when the distance is short and the layout is simple. In the present case, this upstream segment is very short and can be safely disregarded in the total pressure drop calculation.

4.4.7 Pressure Loss Due to Air-only

One of the most significant sources of pressure drop in pneumatic conveying systems is the friction between the moving air and the internal surface of the pipe along straight sections. This frictional resistance reduces the pressure available to maintain product flow and must be accounted for when sizing the air mover.

The pressure loss due to friction is calculated using the Darcy–Weisbach equation (Brown, 2002):

$$\Delta p_{\text{air-only}} = f \cdot \frac{L_{eq}}{D} \cdot \frac{\rho_{air} \cdot C_1^2}{2} \tag{4.6}$$

Where $\Delta p_{\text{air-only}}$ is the pressure loss due to friction [Pa], f is the friction factor [-], L is the equivalent pipe length [m], D is the internal diameter of the pipe [m], ρ_{air} is the air density [kg/m^3] and C_1 is the conveying air velocity [m/s].

To determine the friction factor f, it is necessary to calculate the Reynolds number, Re, which characterizes the flow regime and indicates whether the flow is laminar or turbulent. The Reynolds number is defined as:

$$\text{Re} = \frac{\rho_{air} \cdot C_1 \cdot D}{\mu_{air}} \tag{4.7}$$

Where μ_{air} is the dynamic viscosity of air [Pa·s]. Using the assumed conditions:

$$\text{Re} = \frac{1.225 \cdot 22 \cdot 0.125}{1.8 \times 10^{-5}} = 187153$$

With the Reynolds number calculated, the friction factor f can be estimated using two alternative methods: a numerical approach based on empirical equations, or a graphical approach using the Moody diagram. For the numerical approach, depending on the flow regime, different empirical correlations are applied:

For laminar flow ($\text{Re} < 2300$), the friction factor is calculated from Hagen-Poiseuille formula:

$$f = \frac{64}{\text{Re}} \tag{4.8}$$

For turbulent flow (Re > 4000), two common correlations are:

- **Blasius equation** – applicable to smooth pipes with Reynolds numbers typically below 10^5:

$$f = 0.3164 \cdot \mathrm{Re}^{-0.25} \tag{4.9}$$

- **Colebrook–White equation** – more general and valid for all turbulent regimes:

$$\frac{1}{\sqrt{f}} = -2.0 \cdot \log_{10}\left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{\mathrm{Re}\cdot\sqrt{f}}\right) \tag{4.10}$$

  This equation is implicit in f and requires iterative solving.

Alternatively, the friction factor can be obtained using the Moody diagram, represented through Figure 4.1, which graphically relates the Reynolds number to the relative roughness of the pipe ε/D. For the stainless steel pipe, the adpoted value for roughness was $\varepsilon = 5\times10^{-6}$ m, according to the manufacturer's technical documentation. With an internal diameter $D = 0.125$ m, the relative roughness is:

$$\frac{\varepsilon}{D} = \frac{5\times10^{-6}}{0.125} = 0.00004 \tag{4.11}$$

Using the Moody diagram, with Re $= 187153$ and $\varepsilon/D = 0.00004$, the friction factor can be read as: $f \approx 0.017$

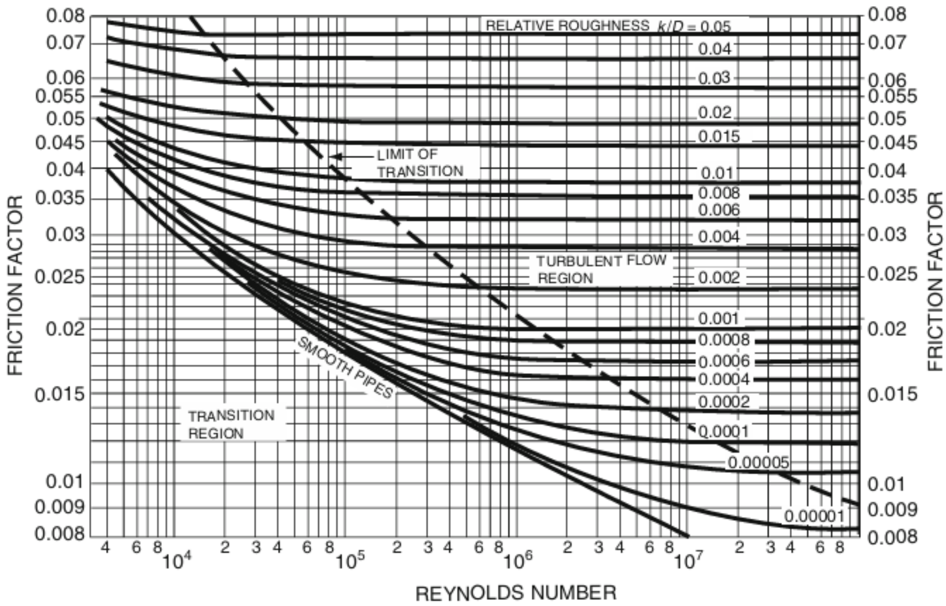

Figure 4.1: Moody diagram (Klinzing et al., 2010).

Mills (2016) states that "an accurate value of a surface roughness is clearly not critical, for a 100% error in relative roughness will only result in a 10 per cent error in friction coefficient". This value reflects the flow conditions in a smooth stainless steel pipe operating under fully turbulent regime. Using this value in the Darcy-Weisbach equation, the pressure loss due to friction along the straight sections of the pipeline can be calculated.

To calculate the total pipeline length L, the concept of equivalent length was introduced. This method consolidates the contributions of various pipeline elements - such as horizontal runs, vertical lifts and bends - into a single effective straight length that reflects the overall resistance to flow. It is widely adopted in pneumatic conveying design to simplify the hydraulic analysis of complex geometries (Brown, 2002).

For vertical sections, a multiplying factor of 2 was applied to the actual length to account for the increased resistance when conveying against gravity. (Mills, 2016).

In the case of bends, the equivalent length depends on its geometry. The defining parameter for bend classification is the ratio between the bend diameter and the internal pipe diameter. In this case:

$$\frac{2r_b}{D} = \frac{2.0}{0.125} = 16.0 \tag{4.12}$$

This places the bends within the long-radius category. For this category, although authors such as Rhodes (2008) recommend values of up to 7.5m and Agarwal (2005) suggests 6m per bend, a equivalent length of 5m per bend was adopted in this study to reflect the relatively smooth configuration of the installation, as suggested by Mills (2016). Thus, the total equivalent length is calculated as:

$$L_{\text{eq}} = L_{\text{horizontal}} + 2 \cdot L_{\text{vertical}} + N_{\text{bends}} \cdot L_{\text{eq,bend}} = 13 + 2 \cdot 17 + 5 \cdot 5 = 13 + 34 + 25 = 72\text{m} \tag{4.13}$$

This equivalent length was then used in the Darcy–Weisbach formulation to determine the pressure drop associated with air-only flow. Substituting in equation (4.6):

$$\Delta p_{\text{air-only}} = f \cdot \frac{L_{eq}}{D} \cdot \frac{\rho_{air} \cdot C_1^2}{2} = 0.017 \cdot \frac{72}{0.125} \cdot \frac{1.225 \cdot 22^2}{2} = 2902.84\,\text{Pa} \approx 0.029\,\text{bar} \tag{4.14}$$

This result corresponds to the pressure loss due to air–pipe wall friction in the straight sections of the conveying line.

4.4.8 Pressure Drop Due to Solids Presence

As explained by Klinzing et al. (2010) and Agarwal (2005), besides the calculation of pressure drop for air-only flow, the additional pressure required to convey the solid particles must now be considered. This contribution encompasses the acceleration of solids to the conveying velocity, the work required to lift them vertically and the additional pressure drop generated by particle–wall and particle-particle interactions.

To provide an integrated estimation of the total pressure requirement, Mills (2016) proposed a semi-empirical expression to calculate the total pressure required at the airmover inlet by accounting for the combined effects of product acceleration, mass flow, air velocity, temperature and pipeline diameter:

$$p = \frac{1}{2}\left\{P_{\text{atm}} + \Delta p_{\text{air-only}} + \left[\left(P_{\text{atm}} + \Delta p_{\text{air-only}}\right)^2 + \frac{\dot{m}_{prod} T \Delta p_{\text{air-only}}}{2.46 C_1 D^2}\right]^{1/2}\right\} \tag{4.15}$$

Where p is the required supply pressure at the air mover inlet [kPa], P_{atm} is the atmospheric pressure [kPa], $\Delta p_{\text{air-only}}$ is the pressure drop due to air-only flow [kPa], $\dot{m}_{prod}$ is the mass flow rate of the product [tonn/h], T is the inlet air temperature [K], C_1 is the conveying air velocity [m/s] and D is the internal diameter of the conveying pipe [m]. Substituting the values:

$$p = \frac{1}{2}\left\{101.3 + 2.9 + \left[(101.3 + 2.9)^2 + \frac{2.0 \cdot 293 \cdot 2.9}{2.46 \cdot 22 \cdot (0.125)^2}\right]^{1/2}\right\} \approx 108.8\,\text{kPa (abs)}$$

The resulting pressure is 108.8 kPa, which corresponds to 1.088 bar (absolute). Subtracting atmospheric pressure ($p_{\text{atm}} = 1.013\,\text{bar}$), the total pressure drop is:

$$\Delta p_{\text{total, Mills}} = 1.088 - 1.013 = 0.075\,\text{bar}$$

While this general formula offers a useful benchmark, the individual contributions of each component previously discussed will be calculated separately in the following subsections to allow for a more transparent and detailed analysis.

4.4.8.1 Pressure Loss Due to Solids Friction

The motion of solid particles suspended in the gas stream results in additional frictional losses, arising from interactions with the pipeline walls and between the particles themselves.

For very low solids loading ratios, frictional losses caused by the solid phase can be considered negligible compared to those caused by the gas. However, for practical design purposes these effects should be included to improve accuracy and reliability. To quantify the contribution of solids–pipe and interparticle friction, one classical approach for incorporating this additional resistance is based on the work of Zenz and Othmer (Agarwal, 2005).

Both Agarwal (2005) and Klinzing et al. (2010) estimate the pressure drop associated with the presence of solids by using an empirical relation, which accounts for the influence of solids loading through a correction multiplier applied to the air-only pressure drop:

$$\Delta p_{\text{solids}} = K \cdot \phi \cdot \Delta p_{\text{air-only}} \tag{4.16}$$

Although the expression above is widely used in pneumatic conveying design, the value of the empirical multiplier K is not constant and varies significantly with particle properties. Raheman and Jindal (2001) demonstrated this variability experimentally for agricultural grains, showing that the solids friction factor depends on multiple flow parameters, including slip velocity, Froude number and the particle-to-pipe diameter ratio. Similarly, Ilari (2002) emphasized that for dairy powders, pressure drop predictions are highly sensitive to operational conditions and product variability, often requiring empirical calibration. Furthermore, Castellanos et al. (2001) reported that fine powders exhibit complex flow behavior due to interparticle forces and wall interactions, reinforcing the need for caution when applying generalized friction corrections.

In the absence of experimental data for milk powder and given its favorable flowability and classification as a Geldart Group A powder, a conservative value of $K = 1.0$ was assumed. This assumption lies within the range reported by Agarwal (2005) (typically 0.4 - 4). Substituting the values:

$$\Delta p_{\text{solids}} = 1.0 \cdot 1.68 \cdot 2900 = 4872\,\text{Pa}$$

Thus, the estimated pressure drop attributed to the frictional interactions of the solid phase is approximately $\Delta p_{\text{solids}} = 4872\,\text{Pa}$.

4.4.9 Pressure Drop Due to Solids Acceleration

When solid particles enter the conveying line, they must be accelerated from rest to their conveying velocity. This process requires energy and results in an additional pressure drop. According to Klinzing et al. (2010), the pressure drop associated with solids acceleration, Δp_A, can be estimated using the following empirical expression:

$$\Delta p_A = \phi \cdot C_1 \cdot \rho_{\text{air}} \cdot C_s \tag{4.17}$$

where ϕ is the solids loading ratio [–], C_1 is the gas velocity [m/s], ρ_{air} is the air density [kg/m^3] and C_s is the solids velocity [m/s].

The solids velocity is not necessarily equal to the gas velocity. Agarwal (2005) suggests that the particle velocity ranges between 70% and 90% of the gas velocity, depending on the material properties. For coarse or granular materials, 80% is commonly assumed. However, for fine powders such as milk powder - which suspend more easily in the gas stream — a value of 90% is often considered appropriate. Therefore, in this study, the solids velocity was estimated as:

$$C_s = 0.9 \cdot C_1 = 0.9 \cdot 22 = 19.8\,\text{m/s} \tag{4.18}$$

Substituting the system parameters ($\phi = 1.68$, $C_1 = 22\,\text{m/s}$, $\rho_{\text{air}} = 1.225\,\text{kg/m}^3$, $C_s = 19.8\,\text{m/s}$):

$$\Delta p_A = 1.68 \cdot 22 \cdot 1.225 \cdot 19.8 \approx 896.50\,\text{Pa}$$

Thus, the pressure drop due to solids acceleration in this system is approximately $\Delta p_A = 896.50\,\text{Pa}$.

An alternative method to estimate the pressure drop associated with solids acceleration was proposed by Agarwal (2005), based on a momentum balance per unit pipe cross-section. Since this empirical correlation is presented in imperial units, it was necessary to perform unit conversions to ensure consistency and accuracy in the calculations. Rather than directly attempting to convert the formula itself to SI units, which could introduce errors due to the complexity of empirical constants, a more reliable approach was to convert the known input variables from SI to imperial units, apply the formula as originally defined, and finally convert the result back to SI units. This method preserves the integrity of the empirical model while allowing direct comparison with other calculations performed in SI. The empirical formula, given in imperial units, is:

$$\Delta p_A = \frac{W \cdot C_s}{4640} \quad \text{[psi]} \tag{4.19}$$

where W is the solids line loading (solids mass flow rate per unit cross-sectional area of the pipe) [lb/s $\cdot$ ft^{-2}] and C_s is the solids conveying velocity [ft/s]. With the already known variables: Solids mass flow rate: $\dot{m}_{prod} = 0.5556\,\text{kg/s}$; Cross-sectional Area: $A = 0.01227\,\text{m}^2$ and Solids velocity: $C_s = 19.8\,\text{m/s} \approx 64.96\,\text{ft/s}$. Solids line loading can be calculated:

$$W = \frac{\dot{m}_{prod}}{A} = \frac{0.5556}{0.01227} \approx 45.28\,\text{kg/s} \cdot \text{m}^{-2} \approx 9.27\,\text{lb/s} \cdot \text{ft}^{-2}$$

And substituting into equation (4.19):

$$\Delta p_A = \frac{9.27 \cdot 64.96}{4640} \approx 0.12978\,\text{psi} \approx 894.80\,\text{Pa}$$

This result is in close agreement with the value obtained using the gas-phase momentum model proposed by Klinzing et al. (2010), which yielded $\Delta p_A \approx 896.50\,\text{Pa}$. The convergence between these two independent approaches reinforces the validity of including this component in the total pressure loss estimation.

4.4.10 Pressure Loss Due to Vertical Elevation

In pneumatic conveying systems, when solids are transported vertically, additional pressure is required to overcome the force of gravity. This pressure required to lift solids vertically can be significantly lower than that estimated using bulk density alone. Klinzing et al. (2010) propose an improved approach that accounts for the actual gas–solid suspension characteristics, where the effective density, ρ^*, is expressed as:

$$\rho^* = \phi \cdot \rho_{\text{air}} \cdot \frac{C_1}{C_s} \tag{4.20}$$

Where ϕ is the solids loading ratio [–], ρ_{air} is the air density [kg/m^3], C_1 is the conveying air velocity [m/s] and C_s is the particle velocity [m/s]. The pressure loss due to elevation is then calculated by:

$$\Delta p_G = \rho^* \cdot g \cdot L_{vertical} \tag{4.21}$$

In this study: $\phi = 1.68$, $\rho_{\text{air}} = 1.225$ kg/m^3, $C_1 = 22$ m/s (design air velocity), $C_s = 19.8$ m/s , $g = 9.81$ m/s^2 and $L_{vertical} = 17m$ (vertical height). Substituting into equations (4.20) and (4.21):

$$\rho^* = 1.68 \cdot 1.225 \cdot \frac{22}{19.8} \approx 2.287\,\text{kg/m}^3$$

$$\Delta p_G = 2.287 \cdot 9.81 \cdot 17 \approx 381.40\,\text{Pa}$$

Alternatively, the pressure drop due to the vertical elevation of solids can also be estimated using the method proposed by Agarwal (2005), expressed in imperial units. As in the previous calculation for solids acceleration, the same approach was applied here. All known input values were converted from SI to imperial units, the original empirical formula was used as published, and the resulting pressure drop in imperial units was then converted back to SI. This ensured a consistent use of the correlation without altering its empirical constants.

$$\Delta p_G = \frac{L_{vertical} \cdot W \cdot g}{144 \cdot C_s \cdot g_c} \quad \text{[psi]} \tag{4.22}$$

where $L_{vertical}$ is the vertical elevation height [ft], W is the solids line loading [lb/s·ft²], $g = 32.2\,\text{ft/s}^2$ is the acceleration due to gravity, C_s is the solids velocity [ft/s], $g_c = 32.174\,\text{ft·lb/lb·s}^2$ is a dimensional constant for unit consistency. Using the system parameters:

$$L_{vertical} = 17\,\text{m} = 55.77\,\text{ft}, \quad W = 9.27\,\text{lb/s·ft}^2, \quad C_s = 64.96\,\text{ft/s}$$

$$\Delta p_G = \frac{55.77 \cdot 9.27 \cdot 32.2}{144 \cdot 64.96 \cdot 32.174} \approx 0.0553\,\text{psi} \approx 381\,\text{Pa}$$

This result is consistent with the estimation from Klinzing et al. (2010), thereby reinforcing the validity of this pressure component in the total system pressure drop assessment.

4.4.11 Summary of Pressure Requirements and Air Supply Considerations

Table 4.6 summarizes the individual contributions to the total pressure drop in the conveying system, based on the previous analytical models. Each value represents the estimated pressure required to overcome the corresponding resistance mechanism.

Table 4.6: Estimated pressure losses in the conveying line using multiple theoretical models

Pressure Loss Component	**Symbol**	**Reference**	**Value [Pa]**
Air–Only	$\Delta p_{\text{air-only}}$	Mills (2016)	2902.84
Air & Solids	$\Delta p_{\text{total, Mills}}$	Mills (2016)	7500.00
Solids friction	Δp_{solids}	Klinzing et al. (2010), Agarwal (2005)	4872.00
Solids acceleration	Δp_A	Klinzing et al. (2010)	896.50
		Agarwal (2005)	894.80
Vertical elevation	Δp_G	Klinzing et al. (2010)	381.40
		Agarwal (2005)	381.00

Based on the values presented in Table 4.6, two approaches were used to estimate the total pressure drop required for the pneumatic conveying system. The first method, proposed by Mills (2016), yields a total pressure drop of:

$$\Delta p_{\text{total, Mills}} = 7500\,\text{Pa}$$

The second method aggregates the contributions individually estimated from multiple sources: the air-only pressure drop, the solids–pipe and interparticle friction, the average pressure drop due to solids acceleration and the average pressure required to overcome vertical elevation.

$$\Delta p_{\text{total, agg}} = \Delta p_{\text{air-only}} + \Delta p_{\text{solids}} + \Delta p_A + \Delta p_G = 2902.84 + 4872 + 895.65 + 381.20 = 9051.69\,\text{Pa}$$

It is important to highlight that these values represent correspond to a theoretical minimum pressure requirement. In real industrial settings, this value is typically increased by a safety margin to ensure reliable operation under varying conditions, such as system wear, dust buildup, product variability or minor blockages. As this system operates in a low-pressure regime, a blower is the most suitable option, as it delivers high airflow at moderate pressure efficiently and cost-effectively. Compressors, on the other hand, are designed for higher-pressure applications and are not justified for this system's requirements. Final blower sizing and supply pressure specification must therefore be validated with the equipment supplier and adjusted according to plant operating practices and safety standards.

4.4.12 Power Requirements and Operating Cost

The power consumption of an air mover is primarily driven by the volumetric flow rate and the pressure it must overcome. Although multiple theoretical models exist to estimate this requirement, the isothermal compression model is adopted here to provide a baseline estimate of the energy required. This approach is commonly used in preliminary design stages due to its simplicity and analytical convenience.

Isothermal compression assumes that the gas is compressed slowly enough to allow continuous heat exchange with the surroundings, thus maintaining a constant temperature. For the purpose of power requirement estimation, the highest pressure drop value obtained ($\Delta p_{\text{total, agg}} = 9051.69\,\text{Pa}$) was adopted. This approach ensures that the sizing of the air mover accounts for the most demanding conditions. Considering that this pressure value corresponds to the required pressure differential across the conveying line, the total absolute pressure at the outlet of the air mover is:

$$p_2 = P_{\text{atm}} + \Delta p_{\text{total, agg}} = 101300 + 9051.69 = 110351.69\,\text{Pa (abs)} \approx 1.1035\,\text{bar (abs)}$$

Mills (2016) presents an empirical formulation for estimating the required power under these conditions:

$$P_{\text{isothermal}} = 202 \cdot Q_{air} \cdot \ln\left(\frac{p_2}{P_{\text{atm}}}\right) = 202 \times 0.270 \times \ln\left(\frac{1.1035}{1.0130}\right) = 4.67\,\text{kW} \tag{4.23}$$

Where $P_{\text{isothermal}}$ is the power required for isothermal compression, Q_{air} is the air flow rate, P_{atm} is the inlet (atmospheric) pressure and p_2 is the outlet pressure of the air mover.

Although theoretical models provide a useful design reference, actual power consumption depends on the specific efficiency of the selected air mover. In industrial applications, equipment must conform to high-efficiency standards. For this system, a motor complying with the IE4 efficiency class is recommended. To estimate the actual input power, these values must be corrected for the motor's efficiency. Assuming an overall system efficiency of 90% (corresponding to high-efficiency IE4-class motors), the adjusted input power becomes:

$$P_{\text{input}} = \frac{4.67}{0.90} = 5.19\,\text{kW} \tag{4.24}$$

Considering a 24-hour daily operation cycle and an average electricity cost of €0.15/kWh, the estimated daily operating cost, $E_{\text{isothermal}}$, is:

$$E_{\text{isothermal}} = 5.19 \cdot 24 = 124.56\,\text{kWh/day} \Rightarrow \text{Cost}_{\text{isothermal}} = 18.68€$$

These values provide a daily cost estimate range depending on the compression model used. To validate the air mover selection and performance, manufacturer literature must always be consulted, including airmover curves, mechanical tolerances and installation constraints.

4.5 Rotary Valve

The rotary valve is one of the key components of the positive pressure pneumatic conveying system, being responsible for the controlled feeding of milk powder into the airflow. Its proper selection is essential to ensure line stability, compliance with ATEX requirements and the hydraulic performance of the system. In the context of this project, it is installed immediately after the weighing conveyor and serves as the transition point between the powder mixture and the airflow generated by the air mover.

In addition to ensuring a stable product flow, the valve must be capable of handling fine powders with a tendency to become suspended , under ATEX conditions, with easy cleaning and industrial-grade reliability for continuous operation.

4.5.1 Manufacturer Selection

The market for rotary valves for pneumatic conveying includes various suppliers offering solutions tailored to different industrial contexts, with variations in design features, certifications, materials and levels of specialization. The selection of the appropriate manufacturer must consider not only the technical requirements of the project but also logistical, maintenance and compatibility factors with the standards of the industrial facility.

In this project, a rotary valve from DMN Westinghouse was required, due to its well-known reliability in the food sector and its compatibility with the criteria required for this project. The main reasons supporting this choice include:

- The brand's established presence in the factory, which facilitates standardization and reduces integration effort;
- The availability of spare parts in stock, minimizing downtime in the event of failure;
- The factory technical team's experience with this brand's equipment, reducing the learning curve and simplifying maintenance interventions;
- The availability of models with ATEX certification for Zone 20 (valve interior);
- Construction in AISI 304 stainless steel with a polished finish, suitable for hygienic design requirements and food contact.

Given the alignment between DMN's offering and the project's operational, safety and maintenance requirements, this brand was considered the most suitable to ensure the robustness, reliability and compliance of the implemented solution.

4.5.2 Comparison Between Drop-Through and Blow-Through Models

DMN Westinghouse offers various rotary valve models for different applications. Among these, the AL and BL series are particularly relevant for pneumatic conveying.

The AL series (Drop-Through) is designed for intermittent feeding and dosing operations. Its simpler construction requires a transition duct to connect with the conveying line, which can lead to dead zones, turbulence and difficulties in cleaning - disadvantages in food-grade environments. Conversely, the BL series (Blow-through) is specifically developed for continuous dilute-phase positive pressure conveying. Its integrated design connects directly with the conveying pipeline, minimizing pressure losses, improving product flow and reducing the number of joints. It offers better feeding performance, especially for fine powders and is available with ATEX Zone 20 certification.

In summary, the BL model meets all project requirements more effectively than the AL, both in terms of functionality and hygiene. Its technical features and optimized geometry make it the preferred solution for this application.

4.5.3 Sizing and Calculation of Rotation

To ensure a continuous and stable feeding of milk powder into the pneumatic conveying line, it is necessary to determine the appropriate rotation speed of the rotary valve. This is based on the required volumetric flow rate of the product and the effective volume handled per revolution by the valve.The production flow rate is given in mass terms, with a design value of $\dot{m}_{prod} = 2000\,\mathrm{kg/h}$. To obtain the corresponding volumetric flow rate, the lowest expected bulk density is used ($\rho_{produ} = 500\,\mathrm{kg/m^3}$), representing the worst-case condition in terms of volume - since it represents the biggest volume for the same mass:

$$\dot{V}_{prod} = \frac{2000}{500} = 4\,\mathrm{m^3/h} \tag{4.25}$$

The required rotation speed is determined using the equation (4.26):

$$RPM = \frac{\dot{V}_{prod}}{V_{rev}} \times 60 \tag{4.26}$$

Where V_{rev} is the effective volume per revolution, calculated as:

$$V_{rev} = V_{theoretical} \times \text{filling efficiency} \tag{4.27}$$

When calculating the effective volume of a rotary valve, 100% of the theoretical capacity of the rotor chamber is not considered, since it is rarely completely filled due to product behavior, filling time and the presence of air. Therefore, a filling factor - known as filling efficiency - is commonly applied, representing the fraction of the volume that is effectively occupied by product. In this project, a value of 70% is considered, according to manufacturer's information. Based on the catalogue data, Figure 4.2, several BL series models were considered, each with different theoretical volumes per revolution.

TYPE				DIN			ANSI		
BL	BXL	Ltr/rev	ØA	ØB	D	ØC	ØB	D	E
150		2,5	150	240	8xØ23	285	241.3	8xØ22.2	12
175	200	5,5	175	270	8xØ23	315	-	-	14
200	250	10,5	200	295	8xØ23	343	298,4	8xØ22.2	14
250	300	19	250	350	12xØ23	406	361,9	12xØ25,4	16
300	350	34	300	400	12xØ23	483	431,8	12xØ25,4	21
350		58	350	460	16xØ23	530	476,2	12xØ28,6	26

Figure 4.2: BL Series Catalogue (DMN Westinghouse)

The Table 4.7 summarizes the calculated rotation speed required for each model, assuming a filling efficiency of 70%.

Table 4.7: Estimated rotation speed for different BL models (filling efficiency = 70%)

Model	Theoretical Volume (L/rev)	Effective Volume (L/rev)	Required RPM
BL150	2.5	1.75	38.1
BL175	5.5	3.85	17.1
BL200	10.5	7.35	9.1
BL250	19	13.3	5.0
BL300	34	23.8	2.8

The results presented allow for an initial filtering of the available options. The BL150 model is excluded due to its high required rotation speed, which may compromise mechanical durability and feeding stability in continuous operation. On the other hand, larger models such as the BL300 and BL350 operate at very low speeds, which may lead to product accumulation, reduced chamber turnover and lower feeding responsiveness.

Both the BL175 and BL200 models fall within a technically acceptable range of rotation speeds and are therefore considered suitable candidates for this application. A final decision between them will depend on additional factors such as integration with existing equipment, mechanical clearance and compliance with hygienic design constraints. To support the final selection, a broader set of qualitative criteria must also be considered, beyond the rotation speed requirements:

- Operational versatility and future scalability: The selected valve must not only meet the current flow requirements but also allow for a safety margin that accommodates slight increases in capacity variations. A valve operating near its limits could present challenges in maintaining stable performance or adapting to future throughput increases. Therefore, models offering flexibility in terms of operational range and robustness under different conditions are preferred;

- Integration with available space and system compatibility: The physical dimensions of the valve and its interface with the conveying pipeline are critical for successful integration into the existing layout. Factors such as alignment with upstream and downstream equipment, ease of maintenance access and structural support must be considered;

- Sustainability and energy performance: Although rotary valves are not high-energy consumers, their design can influence the overall efficiency of the conveying system. Features such as optimized internal geometries, reduced leakage rates and minimized pressure drop across the valve contribute to lower energy consumption and improved system sustainability.

These parameters will be further evaluated in the next phase of the project in collaboration with the equipment supplier, ensuring that the final selection meets both technical and operational expectations.

4.6 Economic Feasibility Assessment

The economic viability of the proposed pneumatic conveying system is evaluated through both its initial investment requirements and long-term operating costs. To evaluate the initial investment required for the implementation of the pneumatic conveying system, a bottom-up cost estimation method was adopted. This approach considers the principal equipment and services involved, providing a more accurate estimate based on the specific technical configuration proposed for the milk powder conveying line. Table 4.8 summarizes the main cost components associated with the project, with typical industrial cost ranges based on supplier information and old quotations received by the company.

Table 4.8: Estimated capital expenditure breakdown for the conveying system.

Component / Service	**Estimated Range (€)**	**Notes**
Blower	5000 – 9000	Depends on flow rate, pressure and acoustic treatment
Blow-through rotary valve	14000 – 18000	Food-grade, hygienic design, ATEX compliance
Control and automation	3000 – 5000	Integration with Ethernet/IP infrastructure
Electrical and instrumentation	2000 – 4000	Cabling, junction boxes, ATEX panels, VFD
Receiving Hopper	1000 - 2000	-
Installation and commissioning	3000 – 5000	-
Project Team related costs	6000 - 8000	Salaries
Total Estimated	**34000 – 51000**	

As addressed in previous sections, the operating costs of the system - mainly driven by power consumption of the blower - were also evaluated, showing a relatively low daily energy cost when considering IE4 motor efficiency and continuous 24-hour operation.

Although a detailed return-on-investment (ROI) calculation is beyond the scope of this design, the combination of technical robustness and strategic alignment with sustainability and safety goals justifies the proposed investment, estimated to be between 34000 € and 51000 €.

Chapter 5

Conclusions, Future Work and Contribution to SDGs

This project aimed to propose a technically viable and structured solution for the redesign of a pneumatic conveying system for milk powder at Nestlé's Avanca plant. The goal was to ensure compatibility with the increased production capacity of 2000 kg/h while improving operational performance, hygienic design and compliance with ATEX requirements.

The work was developed through several phases: understanding the production context and regulatory constraints, assessing the limitations of the current system, reviewing alternative technologies, defining technical specifications and performing preliminary sizing of key components such as the air mover and rotary valve. This culminated in the drafting of a comprehensive User Requirement Specification, serving as a structured basis for supplier consultation.

The technical analysis validated the use of a dilute-phase pneumatic conveying system under positive pressure as the most appropriate option for the application. This choice is supported by the widespread industrial adoption of dilute-phase systems, largely due to their simpler modeling, better predictability, and broader supplier support. In contrast, dense-phase systems remain more complex and empirically designed, making them less suitable for the context of this project.

The pressure drop calculations, which were essential for component selection, highlighted the variability among available models in the literature. The lack of standardized references means that final values are often dependent on the chosen methodology. Furthermore, it was noted that pressure losses may also occur in short sections - such as inside the rotary valve and in the duct between the air mover and the valve - which were not explicitly accounted for in the preliminary calculations. These should be considered during the final design validation.

One practical observation made during the project was the factory's strong reliance on supplier proposals, often without detailed internal verification of air mover specifications. Since suppliers tend to include generous safety margins in their calculations, this can lead to the selection of oversized equipment, which increases both acquisition and operating costs. A more critical internal assessment of such proposals is recommended in future projects to ensure better cost-performance balance.

The proposed system supports a 54% increase in line capacity, rising from 1300 to 2000kg/h, and was shown to be technically adequate to meet production requirements. In addition, it significantly reduces operational and legal risks by ensuring compliance with ATEX regulations. However, all calculations presented in this thesis should be regarded as first approximations. Final equipment selection, validation, and optimization must be carried out in close collaboration with suppliers and supported by detailed design reviews and on-site testing.

A relevant limitation encountered during the study was the lack of detailed information regarding the physical properties of the conveyed powder. Characteristics such as particle size distribution, shape, and cohesiveness were not available, which prevented the accurate calculation of the saltation velocity. As a result, the design was based on assumed air velocities within a safe and typical range, rather than on precise product-specific data.

Beyond addressing the initial problem, this project contributed to the development of relevant technical competencies in system design, pneumatic conveying, safety engineering, and specification drafting. It also provides a useful methodology for future engineering initiatives related to powder handling systems at the factory.

Looking ahead, several opportunities for future work and system improvement have been identified. The first step is to support the implementation and commissioning of the proposed system. This includes assisting during manufacturing, installation, and start-up, to ensure correct integration into the existing process. Once operational, it will be important to collect real-time data on pressure drops, flow stability, and energy consumption to evaluate the system's performance under actual working conditions.

Further technical refinements could include the assessment of adiabatic compression effects. While this study adopted an isothermal model for simplicity, real-world compression often leads to temperature increases that may affect both product quality and power requirements. A more in-depth analysis of these thermal effects could lead to improved design accuracy and process efficiency.

Additionally, the methodology developed in this project can be applied to other pneumatic systems within the plant. This includes the evaluation of potentially over-dimensioned existing lines and the analysis of motor replacement opportunities. It may also serve as a preliminary approach for future production line design, ensuring technically robust and energy-efficient solutions from the outset.

Another area for future exploration is the optimization of pipeline layout. Revising the pipe diameter and route could contribute to a reduction in energy consumption by minimizing pressure losses.

Finally, this work may inspire broader improvement initiatives focused on sustainability, operational resilience, and long-term efficiency. Action plans derived from this study could contribute to Nestlé's strategic goals in reducing environmental impact and enhancing technical performance. These follow-up efforts will not only reinforce the soundness of the proposed solution but also enable the company to align future investments with operational excellence and sustainable manufacturing objectives.

Contribution to the Sustainable Development Goals (SDGs)

This dissertation aligns with several of the United Nations Sustainable Development Goals (SDGs), demonstrating how technical industrial projects can actively contribute to global efforts toward sustainability. The proposed redesign of the pneumatic conveying system, while framed within a local context, incorporates principles that directly support environmental, social and economic sustainability. By integrating energy-efficient equipment, ensuring compliance with safety directives (ATEX) and promoting hygienic design, this work reflects a multidisciplinary commitment to responsible engineering. Table 5.1 summarizes the relevant SDG's supported by the project.

Table 5.1: Relevant Sustainable Development Goals

SDG	Goal	Contribution	KPIs
3	Good Health and Well-being	Enhanced hygienic design reduces the risk of contamination, improving food safety and worker health conditions.	Average cleaning time (min/cycle), Frequency of contamination-related stoppages (incidents/month)
7	Affordable and Clean Energy	Adoption of energy-efficient equipment (IE4 motors) helps reduce electricity consumption.	Specific energy consumption (kWh/kg of powder conveyed), Installed motor efficiency class
9	Industry, Innovation and Infrastructure	Upgrade of legacy systems with modern, ATEX-compliant and sustainable technology promotes resilient industrial infrastructure.	Replacement rate of obsolete equipment (%), Mean Time Between Failures after upgrade (hours)
12	Responsible Consumption and Production	Redesigning minimizes product losses and energy waste, encouraging more responsible use of resources.	Product loss rate during transport (% of total mass), Overall Equipment Effectiveness (%)

This project shows that even technical industrial projects can meaningfully contribute to global sustainability frameworks. Through targeted improvements in energy usage, hygienic standards and system modernization, the project reflects an engineering approach aligned with SDG values. These improvements not only enhance performance but also foster long-term resilience and responsible resource use. The indicators proposed offer a starting point for future tracking and optimization aligned with the company's sustainability goals.

Bibliography

Agarwal, A. T. (2005). Theory and design of dilute phase pneumatic conveying systems. *Powder Handling and Processing*.

Barber, A. (1997). *Vacuum and Low Pressure*. Butterworth-Heinemann, 8th edition.

Brown, G. O. (2002). The history of the darcy-weisbach equation for pipe flow resistance. *Environmental and Water Resources History*.

Castellanos, A., Sánchez, M., and Valverde, J. (2001). The onset of fluidization of fine powders in rotating drums.

Couper, J. R., Penney, W. R., Fair, J. R., and Walas, S. M. (2005). Chapter 20 - gas-solid separations. In *Chemical Process Equipment (Second Edition)*. Gulf Professional Publishing, Burlington.

Cruz, F. (2017). Transporte pneumático de granulados em fase diluída: Estudo e dimensionamento de sistemas industriais. Master's thesis, Universidade do Porto.

Fellows, P. (2009). *Food Processing Technology: Principles and Practice*. Woodhead Publishing, 3rd edition.

Geldart, D. (1973). Types of gas fluidization. *Powder Technology*.

Geldart, D., Abdullah, E., Hassanpour, A., Nwoke, L., and Wouters, I. (2006). Characterization of powder flowability using measurement of angle of repose. *China Particuology*.

Gomide, R. (1983). *Operações com Sistemas Sólidos Granulares*, volume 1. Edgard Blücher, São Paulo.

Ilari, J. (2002). Flow properties of industrial powder. *Lait*.

Instituto Nacional de Estatística (2024). Estatísticas Agrícolas 2023.

Klinzing, G., Rizk, F., Marcus, R., and Leung, L. (2010). *Pneumatic Conveying of Solids: A Theoretical and Practical Approach*. Particle Technology Series. Springer Dordrecht, 3 edition.

Klinzing, G., Rohatgi, N., Zaltash, A., and Myler, C. (1987). Pneumatic transport — a review (generalized phase diagram approach to pneumatic transport). *Powder Technology*.

Malekjani, N. and Jafari, S. M. (2023). Introduction to food material handling within food factories. In Jafari, S. M. and Malekjani, N., editors, *Transporting Operations of Food Materials Within Food Factories*. Woodhead Publishing.

Mills, D. (2016). *Pneumatic Conveying Design Guide*. Butterworth-Heinemann, 3rd edition.

Mills, D., Jones, M. G., and Agarwal, V. K. (2004). *Handbook of Pneumatic Conveying Engineering*. CRC Press, Boca Raton, 1 edition.

Nestlé Portugal (2024). Nestlé Portugal prepara futuro e reforça presença em Portugal. https://empresa.nestle.pt/media/comunicados/2024-nestle-reforca-posicao-portugal.

Nestlé S.A. (2025). An overview of nestlé for investors. https://www.nestle.com/investors/overview.

Raheman, H. and Jindal, V. K. (2001). Pressure drop gradient and solid friction factor in horizontal pneumatic conveying of agricultural grains. *Applied Engineering in Agriculture*.

Rhodes, M. (2008). *Introduction to Particle Technology*. Wiley, 2nd edition.

Scheibel, M. (2018). Estudo numérico-experimental do escoamento em transporte pneumático de fase diluída. Msc thesis, Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil.

Solt, P. (2001). Conveying bends: Design, selection and application. Technical report, Pneumatic Conveying Consultants.

Werther, J. (1987). D. geldart (ed.): Gas fluidization technology, john wiley & sons. chichester, new york, brisbane, toronto, singapore 1986. *Berichte der Bunsengesellschaft für physikalische Chemie*.