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Powder-Logistics Concept for Future LPBF High-Volume Shop

Developing a scalable powder-logistics concept for serial
LPBF production

Master's thesis in Supply Chain Management

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Abstract

Following the increasing use of additive manufacturing in aerospace production, Laser Powder Bed Fusion has become an important technology for producing complex and lightweight metal components. However, scaling LPBF from a low-volume demonstration environment to high-volume serial production creates new requirements for powder-logistics. Metal powder must be handled safely, traceably and efficiently, while risks related to manual handling, contamination, ergonomics and tied-up capital need to be controlled.

This study investigates a company within the aerospace industry that is preparing a future high-volume LPBF production facility. The current powder-logistics setup is mainly designed for low-volume development and learning and is therefore not suitable for the expected increase in production volume, material movements and parallel powder flows. Therefore, this study aims to support the company by developing and evaluating a powder-logistics concept that enables safe, traceable, cost-efficient and scalable operations.

Through observations, interviews, internal data, workshops, Material Flow Mapping and Systematic Layout Planning, several limiting factors were identified and analyzed. These included manual handling, unclear storage logic, high handling frequency, traceability requirements, operational risks and the need for future scalability. To address these factors, a final powder-logistics concept is proposed. The concept includes a structured cell-based layout, larger powder units, defined storage and filling zones, improved identification systems, lifting support and is automation-ready.

By implementing the proposed concept, the company can reduce handling complexity, improve traceability and operator safety, and create a scalable structure that can be multiplied as production volume increases.

Keywords: LPBF, additive manufacturing, powder-logistics, material flow, aerospace, layout planning, scalability.

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We would also like to thank the studied company, our company supervisor and all involved employees for their time, support and guidance throughout the project. Their knowledge, experience and valuable insights have been essential for understanding the studied production environment and developing the proposed powder-logistics concept.

Sincerely,
Pontus Larsson and Elise Mellbin, May 2026

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1. Introduction

This chapter introduces additive manufacturing (AM) and its growing role in aerospace production, with a specific focus on Laser Powder Bed Fusion (LPBF) and the importance of effective powder-logistics in high-volume environments. It presents the studied company and the studied production context, outlining the background to the planned future LPBF production site. Furthermore, the chapter defines the problem addressed in the study, states the aim of the thesis, and clarifies the study's delimitations to establish a clear scope for the work.

1.1 Background

In today's unpredictable global environment characterized by trade disputes, conflicts and pandemics, companies must ensure the resilience of their supply chains. Peron, Saporiti, Coruzzolo, Lolli, and Holmström (2025) states that this often requires reducing dependence on external suppliers and improving the ability to respond quickly to disruptions. Peron et al. (2025) continue and explains that one effective strategy for enhancing resilience is the adoption of AM and that during the COVID-19 pandemic, AM proved particularly valuable, enabling the rapid production of essential components close to where they were needed. The studied company wants to be in the forefront of this development. The company is a global aerospace company with roots dating back to the Industrial Revolution. Over the years it has evolved from traditional industrial manufacturing into a leading supplier of advanced aerospace structures, engine components and systems for both commercial and military aircraft worldwide. The company has further strengthened its global presence through strategic acquisitions. The studied company operates in 12 countries with approximately 16,000 employees with innovation always at the heart of its operations (The studied company 2025). A key site is Sweden, home to the newly established department for AM. The strategy for this department is to redefine how materials are supplied within the aerospace industry, by replacing traditional castings and forgings with solutions that incorporate AM (The studied company, internal document, 2025).

Despeisse, Hajali, and Hryha (2024) outline that AM, also known as 3D printing, is today widely adopted across industries and is a key component of industry 4.0. Despeisse et al. (2024) further explain that its early history dates to 1951 when Otto John Munz patented the foundational principles of AM and that it since then has evolved significantly and is now used in applications for high-technology sectors such as aerospace where it is used for producing complex and lightweight components. Chowdhury, Yadaiah, Prakash, Ramakrishna, Dixit, Gupta, and Buddhi (2022) clarify that among the different AM processes, LPBF has emerged as a leading method for metal components and since the development in the 1990s, LPBF has evolved in response to demand from industries such as aerospace. Chowdhury, et al. (2022) explains that in this process, metal powder serves as a feedstock and is selectively melted by a laser from a "melt pool" that solidifies shortly afterward. Chowdhury, et al. (2022) states that LPBF eliminates several steps required in traditional manufacturing such as tool changes and allows complex parts to be produced in a single build without assembly. Another advantage of LPBF explains Chowdhury, et al. (2022) is material efficiency as unused powder can be recycled for future build, reducing waste and lowering production costs while benefiting the environment.

Dugheri, Cappelli, Trevisani, Kemble, Paone, Rigacci, Bucaletti, Squillaci, Mucci, and Arcangeli (2022) explain that while LPBF offers significant advantages such as design freedom and sustainability benefits, the process also introduces health and safety problems. Dugheri et al. (2022) further note that compared to conventional manufacturing methods, LPBF involves extensive manual work, particularly in the pre- and post-processing steps such as powder loading and powder recycling. During these operations, operators handle fine metal powders (20–60 μm) which can be inhaled or encounter the skin, potentially causing inflammatory responses and long-term health effects. Similarly, Mossa, Boenzi, Digiesi, Mummolo, and Romano (2016) emphasize that human labor is still widely relied upon to provide the flexibility that full automation cannot always achieve and many production processes therefore continue to involve extensive manual work. Mossa et al. (2016) highlight that in such contexts and when the production is scaled up the physical workload on workers rises correspondingly. Mossa et al. (2016) also mentions that this increase in workload can raise the risk of work-related musculoskeletal disorders (WMSDs) in repetitive manual tasks.

Companies in today's competitive landscape often choose to scale up production to achieve economies of scale. In simple terms, this means that by producing more, the total costs are spread over a larger number of products which lowers the cost of each individual item (Lim & Malhotra, 2024). However, Al-Zubaidi, Fantoni, and Failli (2021) explain that scaling up production requires careful consideration of operational efficiency and facility layout, as material handling can account for up to 50% of total operating costs and that a well-designed layout can reduce these costs by as much as 30%. In addition, an effective layout provides a foundation for efficient resource utilization and contributes to high levels of safety and worker well-being within the factory. (Al-Zubaidi et al., 2021). According to Huang, Guo, Li, Zhao, Wang, and Li (2025), early conceptual design helps ensure that the layout and material flow are planned according to system requirements while also supporting innovation. Conceptual design, defined by Huang et al. (2025) is an early stage in which initial high-level solution ideas are developed based on system requirements which provides the foundation for innovation, prevents defects and reduces costs in later design stages.

1.2 Problem description

The studied company is preparing a high-volume LPBF production site for serial production, characterized by higher throughput, more frequent powder movements and multiple machines. In practice, this means more material moves per shift, more simultaneous jobs, and more handovers between people/system. The new workshop will build on experience from the current demonstration facility in Trollhättan. The Trollhättan facility operates at low volumes, meaning that it is primarily used for process development, testing and learning rather than continuous serial production. In this context, low volume refers to a production environment with few LPBF machines, limited parallel production, lower build frequency, and less frequent powder movements compared with the planned high-volume shop. The current facility has two AM machines, one for titanium powder and one for Inconel powder, which means that powder-logistics activities are performed at a smaller scale and with fewer simultaneous material flows than would be expected in serial production.

While the current setup has enabled learning and process validation, powder-logistics is largely manual and resource-intensive. In this study, powder-logistics refers to the internal flow and management of metal powder from receipt to reuse-ready material, including storage, internal transport, machine filling and the reuse loop. Several steps expose operators to health and safety risks (e.g., inhalation, skin contact, and fire/explosion hazards), require extensive protective measures, and involve ergonomically demanding manual handling. As a result, the current approach is not suitable for scalable, high-volume production.

To enable high-volume production, the studied company needs a standardized powder-logistics concept that meets requirements for safety, contamination control, ergonomics and traceability. In this study, the powder-logistics concept describes the proposed future-state system for powder handling within the planned high-volume LPBF production environment. The concept includes the complete powder flow from inbound goods reception to storage, filling and powder recovery. It also defines the operational structure of the powder-handling process, including process interfaces, powder batch strategies, internal transport principles and traceability routines. The concept also includes layout considerations for powder-logistics activities and areas (e.g., storage locations and transport routes), while machine layout and placement are predetermined and therefore outside the scope of this concept. The studied company has initiated evaluation of automated powder-logistics solutions, such as AMR/AGV-supported transport, to reduce manual handling and improve safety and efficiency.

Building on these initial efforts, there is a clear need to define a standardized powder-logistics concept that supports the transition to high-volume LPBF production. This study therefore focuses on establishing such a concept, providing a foundation for scalable and efficient powder handling in the future workshop.

1.3 Aim

The aim of this study is to support the decision making of powder-logistics for the studied companies planned high-volume LPBF facility by mapping the current process, consolidating cross-functional

requirements and evaluating alternative concepts (including layout and internal material-flow options). The study will recommend a powder-logistics concept that is cost efficient while ensuring safe, traceable, and scalable operations.

1.4 Delimitations

This study is limited to the logistics configuration and evaluation of powder-logistics concepts for the planned high-volume LPBF shop, focusing on operational flow and planning-level decisions (layout comparison and recommendation). Furthermore, the study does not address detailed engineering design of equipment beyond planning-level concepts, nor does it include supplier selection/procurement negotiations and detailed cost modeling beyond decision-support estimates. While the results of this study may offer insights relevant to other companies operating high-volume LPBF facilities, the primary focus is on the studied company and the specific conditions of its planned production environment.

2. Methodology

This chapter presents the methodological approach used to develop and evaluate a powder-logistics concept for a future high-volume LPBF production environment at the studied company. The study combines qualitative data collection methods with logistics and layout-planning tools to analyze current powder-logistics processes, identify system requirements and develop feasible logistics configurations. The methodology is structured around the Environment–Performance–Logistics (EPL) framework and principles from Systematic Layout Planning (SLP) which together support the development and evaluation of alternative concepts based on efficiency, cost and operational risk.

2.1 Research Approach and Design

This study is designed to support the studied company in developing a powder-logistics concept for a planned high-volume LPBF shop. The research problem is practical and context-dependent, as powder-logistics in the aerospace industry must balance cost and capital efficiency with requirements such as contamination control, traceability, and safe operations.

Figure 2-1 illustrates the Environment-Performance-Logistics (EPL) framework, which serves as the analytical foundation of this study. The framework is built on the interaction between logistics configuration and system performance, where the developed concept emerges at their intersection. Logistics configuration encompasses key design dimensions such as layout, material handling and automation while performance is evaluated through KPIs such as efficiency, cost and safety. These elements are inherently interdependent where configuration choices directly dictate performance outcomes, while performance requirements and the environmental requirements act as the guiding criteria for selecting the configuration.

Central to this framework is the environment, which acts as the outer boundary for the entire system. The framework recognizes that there is no "one-size-fits-all" solution and instead the logistics system must be a direct response to its specific context. In this study, the environment represents the studied company's fixed constraints.

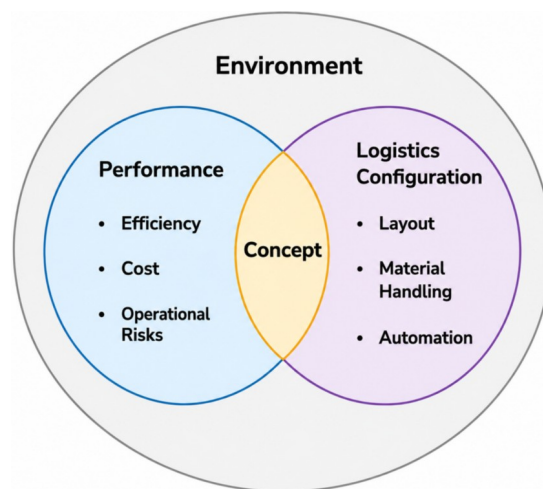


Figure 2-1 EPL Framework, own illustration.

To operationalize the Environment-Performance-Logistics (EPL) framework, this study is structured into four interconnected stages. This structure ensures that the final logistics concept is not only theoretically grounded but also operationally feasible within the specific context. Table 2-1 gives an overview of the stages.

Table 2-1 Methodological stages.

Stage	What is done?	How is it done?	Aim
Theoretical Foundation	Establish a theoretical framework for the study	Literature review	Identify best practices and established design parameters
Environment	Map the current state and identify system limitations.	Data collection (interviews, observations), Material Flow Mapping (MFM) and Environment Workshop	Create a requirements profile and identify fixed environmental constraints
Logistics Configuration	Develop conceptual layout alternatives	Systematic Layout Planning (SLP), relationship analysis, and iterative concept generation	Create configurations that match the identified requirements
Performance	Evaluate and compare the proposed concepts	Performance analysis via KPIs (cost, safety, efficiency), Spider diagrams and Evaluation Workshop	Select the most suitable powder-logistics configuration for the studied company

2.1.1 Qualitative Design

Business research is described by Bell, Bryman and Harley (2022) as either quantitative or qualitative, depending on what type of data is emphasized and how the research seeks to generate knowledge. Bell et al. (2022) explain that quantitative research is typically associated with the collection and analysis of numerical data, while qualitative research is associated with the collection and interpretation of data consisting of words, meanings and other non-numerical forms such as documents and observations. Since the objective of this study is to understand requirements, constraints and trade-offs related to powder-logistics in high volume, a qualitative research strategy is considered most suitable. However, the study also uses available production data, supplemented with informed assumptions where necessary, to support the assessment of factors affecting the standardized powder-logistics concept. This approach ensures that decisions are grounded in both real operational data and reasonable estimates. The study is primarily guided by inductive logic described by Bell et al. (2022) as a research logic where theory and understanding are developed through engagement with empirical observations and findings, rather than starting from a predefined hypothesis.

Therefore, the study follows a primarily qualitative and inductive logic, complemented by quantitative estimates where needed to compare alternative concepts regarding cost and tied-up capital in powder. This approach enables an in-depth understanding of the current powder-logistics practices, operational constraints and improvement opportunities, while keeping the analysis grounded in the realities of the intended production environment.

2.2 Literature Review

A targeted literature review is conducted to establish a theoretical foundation for the study and to support the development and evaluation of a powder-logistics concept. In this study, the theoretical foundation refers to the set of existing concepts, principles, and research findings that provide a structured basis for analyzing and designing a powder-logistics concept. It helps define the key dimensions that must be considered when developing the concept, such as facility layout, material flow, traceability, safety, and

cost efficiency. The literature review helps identify existing knowledge, common challenges, and best practices within these areas, thereby providing a structured starting point for the study. The relevant literature was mainly obtained via Chalmers Library and Google Scholar. Esaiasson, Gilljam, Oscarsson, Wängnerud, and Towns (2017) emphasize the importance of reviewing previous research and relevant theory early in the research process to gain an overview of existing knowledge and established best practices. Such a review helps clarify the extent to which the topic has already been studied and identifies useful starting points for the project. However, Esaiasson et al. (2017) also point out that this process can be time-consuming and that locating relevant and reliable information on a specific subject can sometimes be challenging.

2.3 Empirical Data Collection

In this section the different methods of data collection are presented. Data is collected from multiple sources to reduce the risk of basing conclusions on a single perspective. The data collection is divided into interviews, observations, workshops and additional secondary data.

2.3.1 Interviews

To identify and understand cross-functional requirements and priorities for a future LPBF production environment, several interviews were conducted with key stakeholders involved in LPBF production and powder-logistics (e.g., operators, engineers, production/quality representatives, and relevant HSE/compliance roles). Careful planning is required before conducting the interviews. First, the selection of respondents must be carried out. Esaiasson et al. (2017) explain, the respondents should be “centrally placed”, meaning they are individuals with significant knowledge or influence regarding the subject under analysis. Typically, the individuals serving as central sources can be identified in advance due to their relevant roles and experience. Once the central sources are identified, a snowball sampling approach can be used where each respondent recommends others who may provide new valuable insights. Esaiasson et al. (2017) also notes that there should be no predetermined limit on the number of respondents and that interviews should continue until no new information that has value emerges.

In this study, to support the aim of capturing cross-functional requirements while still allowing new issues to emerge, the interviews are conducted as semi-structured interviews. Bell et al. (2022) describe semi-structured interviewing as an approach where an interview guide is used to ensure that key topics are covered across respondents, while the interviewer still has flexibility to vary question order, follow up on interesting points, and introduce additional questions when relevant. This flexibility is highlighted as a key feature of qualitative interviewing, since it allows the interview to follow the direction of the respondent and adapt to important issues that arise during the conversation. For this study, a semi-structured format is therefore appropriate because it balances comparability between different stakeholder groups with the ability to explore role-specific constraints, priorities, and examples in depth (Bell et al., 2022).

Creating a supportive and open atmosphere is, according to Esaiasson et al. (2017), crucial for interviews because it encourages respondents to share their experiences and provide meaningful insights. Esaiasson et al. (2017) also states that questions should be straightforward to prevent confusion or the need to clarify terminology and that effective interview questions are generally concise to encourage detailed responses. In addition, Esaiasson et al. (2017) emphasize that questions should avoid being overly complex or leading, allowing participants to express their own perspectives freely. Interviews are typically structured around several themes, following recommendations by Esaiasson et al. (2017). The first theme consists of “get to know you” questions, designed to help the respondent feel comfortable and engaged. These may include questions about the person's role and for how long they have worked in that position. Following this are the thematic questions focusing on exploring key topics such as constraints or challenges in the current LPBF demonstrator which form the foundation of the interview. Esaiasson et al. (2017) continue and explain the follow-up questions that are used to gather additional details or clarify gaps in earlier responses. These could for example be “You mentioned challenges with powder-logistics, can you describe a specific situation?”. Finally, the interviewer may ask direct questions to ensure that all key topics have been explored in sufficient depth, in line with recommendations by Esaiasson et al. (2017).

2.3.2 Secondary Data

Secondary data refers to information that has already been collected by other researchers, companies or organizations for a different purpose and being reused (Bell et al., 2022). Secondary data play a central role in this study by supporting the development of an in-depth understanding of the LPBF process and by providing a foundation for layout and logistics proposals for powder-logistics in a future high-volume production environment. The study primarily uses existing internal data from the studied company's demonstration facility, together with operational measurements and production data from the factory. This data may include process flows, material consumption rates and handling times. This data enables a good analysis of workflows, resource use and material movements to identify constraints, risks, performance limitations and potential areas for improvements. By interpreting this existing information, the study can build on accumulated operational experience and ensure that the proposed powder-logistics concept is grounded in real production conditions and operational experience, rather than assumptions.

2.3.3 Current state and material flow mapping

To understand the current state and the constraints of the new powder logistics system a detailed overview of the current process was done. This was done through interviews, current state mapping, observations and internal documents.

First a flowchart of the powder-logistics process was created to visualize the specific steps involved. The flowchart, as described by Damelio (2011), provides graphic representation of the workflow from start to finish with all necessary steps mapped. Damelio (2011) explains that the flowchart can help identify inefficiencies and potential bottlenecks in the process. When creating the flowchart, Damelio (2011) emphasizes that it is first important to define the scope, in this case focusing exclusively on powder-logistics. Damelio (2011) further explains that the different steps should then be organized in a logical sequence, typically moving in one direction such as from left to right to reflect the actual order of operations. Standard symbols are used to represent the various activities, decisions and outputs making the process easy to follow, as outlined by Damelio (2011). The mapping scope covers powder from arrival at the Sweden site gates to support activities linked to finished product output, including the reuse of unused powder. The current-state map was created using data from observations, complemented by internal process documentation and stakeholder input where available. Figure 2-2 illustrates an example of how a flowchart could be organized based on Damelio (2011).

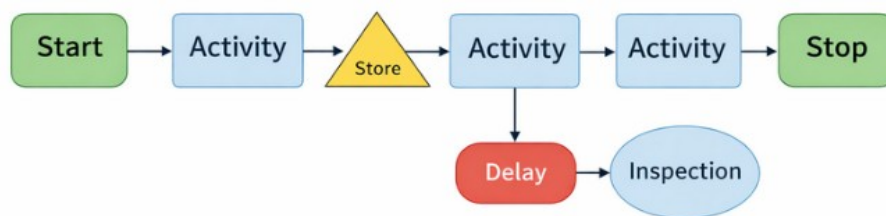


Figure 2-2. Flowchart. Own illustration, based on Damelio (2011).

While the flowchart provides an overall view of the process, Material Flow Mapping (MFM) was used to examine the logistics configurations in more detail and support the analysis with quantitative measurements. MFM is a tool used to understand and analyze how materials move through a supply chain, especially when supplying materials to assembly (Finnsgård et al., 2011). It was developed from Value Stream Mapping (VSM) to better fit material supply systems. Traditional VSM mainly focuses on manufacturing and highlights activities that add value to a product. However, in material supply, very few activities add value. Most tasks are necessary but do not directly improve the final product. MFM helps solve this problem by showing these non-value-adding activities in more detail. This makes them easier to see and improve.

Finnsgård et al (2011) explain how MFM is a simple way to group all material flow activities into four types, called HATS:

Handling (H): Moving or rearranging materials in the same place, such as repacking or shifting items between containers.

Administration (A): Information tasks like scanning barcodes, using kanban cards, or entering data into a system.

Transportation (T): Moving materials from one location to another, such as between buildings or departments.

Storage (S): Any time materials are waiting or being stored, even for a short time.

Research shows that when materials pass through extra steps or multiple stages, the amount of handling and administrative work increases a lot (Hansson et al., 2011). By measuring these activities, the study can identify the current state and how our logistics configurations change the number of activities.

2.3.4 Environment Workshop

To develop different logistics configurations the findings from the environmental analysis had to be combined into key problem areas and design requirements. These were presented in a first workshop with cross-functional stakeholders which are listed in Table 2-6, chapter 2.6. The primary objective of this workshop was to define a stable, safe and scalable powder logistics flow for the transition to the new high-volume LPBF facility and gather more constraints from the environment. The goal was to determine how the powder could flow depending on different stakeholder's opinions and insights from the arrival of goods to the point where the powder is in the reuse loop by identifying realistic goals, previously missed risks and feasible solutions for a high-capacity environment.

The workshop was structured around several key areas of the powder logistics chain, starting with a material flow mapping of the current process. Participants then evaluated four critical dimensions for change which included container volume, the physical filling point of the material, the degree of automation and the implementation of intermediate storage buffers. The combination of these variables allowed for the exploration of what these different alternatives would mean for the stakeholder's daily operations and what specific impact they would have on their areas of responsibility. For each alternative, stakeholders could state the strengths and weaknesses that they could identify such as ergonomic risks or the overall impact on their day-to-day work. This methodical approach aligns with how workshops are described by Denecke, Rivera-Romero, Giunti, Van Holten and Gabarron (2025) to include various stakeholders in the design process and integrate multiple perspectives in the creation of solutions that are aligned with real operational needs. A similar idea is described by Palange and Dhattrak (2021) through the concept of "Quality Circles," where groups collaborate to generate ideas and drive improvements.

Denecke et al. (2025) presents a framework for conducting successful workshops, consisting of a couple key components. These include defining the purpose and objectives of the workshop, participant selection, as the success of a workshop largely depends on the individuals involved and their respective expertise. In addition, Denecke et al. (2025) outline that the framework highlights the role of the facilitator in guiding the process, including managing power dynamics and establishing shared rules to ensure balanced participation. Denecke et al. (2025) also underlines the importance of the workshop setting, ensuring that the environment supports effective collaboration. Finally, Denecke et al. (2025) emphasize that ethical considerations and regulatory compliance are essential aspects to ensure that the workshop is conducted in a responsible and appropriate manner.

Following the initial workshop, a comprehensive understanding was established regarding the practical implications of different logistics configurations and how they would specifically impact stakeholders' daily operations. By evaluating the strengths and weaknesses of various configurations such as larger

container volumes, external filling points and automated transport systems, the project was able to identify realistic goals, previously unrecognized risks like ergonomic strain and the necessary support measures required for a high-volume environment.

2.4 Logistics configuration development

This chapter presents the theoretical framework used to support the development of logistics configurations in this study. It is primarily based on the principles of Systematic Layout Planning (SLP) as described by Muther and Hales (2015). The chapter outlines the key concepts, steps and tools within SLP, including the identification of activities, relationship analysis and the development and evaluation of layout alternatives. Together, these elements provide a structured approach for designing and comparing different layout configurations.

2.4.1 Systematic Layout Planning

The development of the logistics configurations in this study was carried out using the principles of Systematic Layout Planning (SLP) described by Muther and Hales (2015). SLP is described as a form of “thought ware” rather than a mathematically driven optimization method, meaning that layout design is based on logical reasoning and a structured step-by-step approach instead of complex calculations. In this study, SLP was applied as a systematic method for developing and evaluating feasible logistics layout alternatives. The method involved analyzing system requirements, identifying functional relationships, generating alternative layouts and evaluating the alternatives based on predefined criteria.

The work started with an analysis of the system requirements based on the SLP input categories explained by Muther and Hales (2015) as P, Q, R, S and T. Product (P) referred to the material and products flowing through the system, Quantity (Q) included production volumes and batch sizes, Routing (R) described how materials moved between processes, Supporting services (S) included storage areas, waste handling and other supporting functions while Time (T) covered aspects such as takt time, production frequency and capacity requirements. The key input data is displayed in Table 2-2. This analysis was used to define what the logistics system and layout needed to support.

Table 2-1. Key Input Data.

P	Product	What is flowing?
Q	Quantity	How much? Volumes, batch sizes
R	Routing	How does it flow?
S	Supporting Services	Inventory, waste
T	Time	Frequency, Takt, Capacity

Based on this analysis, the main functional areas and processes within the logistics system were identified. The relationships between these areas were then analyzed to determine which processes should be located close to each other to support efficient material flow and operational coordination. Focus was placed on reducing unnecessary transport distances and ensuring that connected processes were positioned logically within the facility. This part of the SLP is referred to as “Relationship Analysis” by Muther and Hales (2015).

After the relationship analysis the available facility space and physical constraints were considered during the development of the layout alternatives. Some configurations were adapted to fit within the existing factory layout while other alternatives were developed more freely to explore potential improvements without being limited by the current facility structure.

Several alternative logistics configurations were then developed by combining process relationships, material flow considerations and practical constraints in different ways. Throughout this process, adjustments were continuously made to ensure that the layouts were feasible and aligned with the operational requirements of the system.

Finally, the developed layout alternatives were evaluated and compared in accordance with the principles described by Muther and Hales (2015). The purpose of this evaluation was to identify the most suitable logistics configuration for the studied system. The steps of the SLP methodology are illustrated in Figure 2-3.

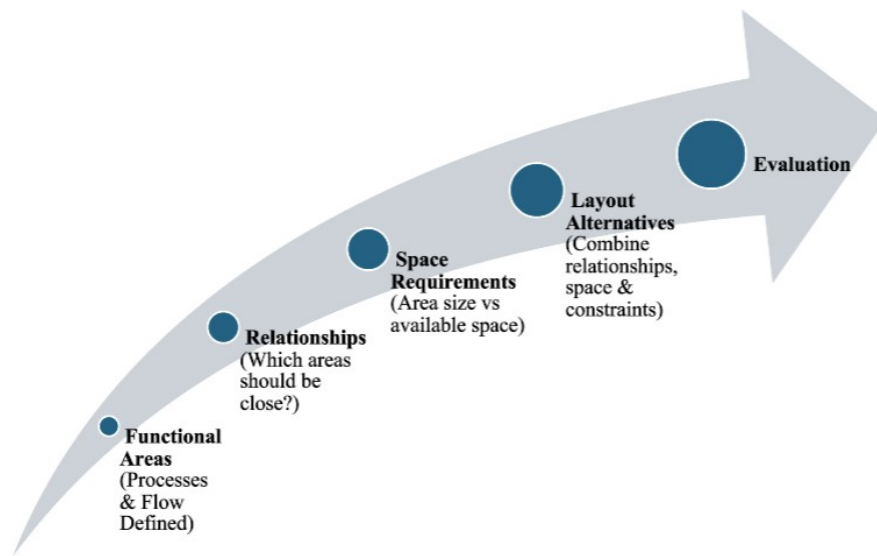


Figure 2-3. SLP Steps based on Muther and Hales (2015)

2.4.2 Activities and Activity Areas

Muther and Hales (2015) highlights that activities can either be combined or split depending on their characteristics and relationships. Combining related activities can improve flow and coordination while splitting activities may reduce complexity and increase flexibility. One example that Muther and Hales (2015) give is the introduction of product focused cells where equipment and processes are grouped based on product flow rather than function. In such cases, all necessary steps for producing a product or product family are brought together within a single area.

As part of the SLP methodology described by Muther and Hales (2015), the activities and functional areas included in the logistics system were identified and defined. According to Muther and Hales (2015), these activities represent the elements that form the basis of the layout design meaning that an accurate definition of the activities is important for developing feasible layout alternatives. In this study, the identified activities included areas such as material receiving, storage, production-related processes and outbound material flows.

Muther and Hales (2015) further emphasize that existing departmental structures should not automatically be considered optimal as they may limit opportunities for improvement. Therefore, the existing process structure and area divisions were critically evaluated during the study rather than being directly transferred into the new layout alternatives. Muther and Hales (2015) also highlights that activities can either be combined or split depending on their characteristics and relationships. Combining related activities can improve flow and coordination while splitting activities may reduce complexity and increase flexibility.

To support the layout development process, a structured activity list inspired by Muther and Hales (2015) was created. The activities were organized according to their order in the operational flow to visualize how materials and processes moved through the system. This activity list served as a basis for the subsequent relationship analysis and the development of layout alternatives. Table 2-3 presents an example of how the activities were structured.

Table 2-2. Example of Activities List based on Muther and Hales (2015)

Order of appearance	Name	Description
1	Entrance	Goods entrance
2	Storage	Raw Material Storage
3	Machine	Production

2.4.3 Relationship Analysis

Following the activity identification, a relationship chart inspired by the methodology of Muther and Hales (2015) was developed to analyze which activities should be located close to each other within the logistics layout. The identified activities were translated into pairwise relationships where each relationship was assigned a closeness rating based on its importance for material flow and operational performance.

The closeness ratings were based on the SLP relationship categories presented by Muther and Hales (2015) where A represented relationships that were considered absolutely necessary while lower ratings represented decreasing levels of proximity importance. Relationships where separation was preferable were assigned an X rating. The assigned ratings were primarily based on material flow intensity, operational dependencies and observations of the existing processes during the study. In addition, the relationship chart was visually supported using the color-coding principles proposed by Muther and Hales (2015) where the different closeness ratings were distinguished by colors to improve readability and facilitate comparison between activities. During the relationship analysis, particular attention was given to avoiding overuse of the highest closeness rating to ensure that only relationships considered critical for the logistics flow were classified as absolutely necessary. Table 2-4 presents an example of how the relationship chart was structured in this study.

Table 2-3. Example of a Relationship Chart based on Muther and Hales (2015).

	Inventory Raw Material	Inventory Finished Goods	Production	Shipment
Inventory Raw Material	-	X (undesirable)	E (especially important)	U
Inventory Finished Goods	X (undesirable)	-	A (absolutely necessary)	I (important)
Production	E (especially important)	A (absolutely necessary)	-	O (ordinary)
Shipment	U	I (important)	E (especially important)	-

2.4.4 Development of Layout Alternatives

Following the relationship analysis, several alternative logistics configurations were developed in accordance with the principles described by Muther and Hales (2015). Rather than focusing on a single solution, the purpose was to explore multiple layout concepts to compare different structural approaches and identify potential improvements within the logistics system.

The development of alternatives was guided by deliberate variations in key layout aspects rather than random rearrangements of activities. Focus was placed on evaluating different material flow structures, positioning of functional areas and alternative routing principles within the facility. The alternatives therefore differed in terms of how processes and flows were organized as well as how closely the configurations followed the limitations of the existing factory layout. Different layout concepts were explored by changing the placement of activities, adjusting material flow directions and testing alternative process groupings to analyze how different structural solutions could affect the logistics performance. In some alternatives, the existing factory structure and current input and output locations were kept, while other alternatives were developed more freely to explore improved flow solutions without the same physical limitations.

Throughout the layout development process, the alternatives were continuously refined and adjusted based on the relationship analysis, material flow considerations and practical constraints identified during the study. In line with Muther and Hales (2015), the layout development process was therefore not limited to rearranging activities but focused on systematically exploring different structural logics and flow principles to identify feasible and effective logistics configurations.

2.4.5 Automation

Automation was considered throughout the logistics configuration development as a potential way to reduce manual powder handling, improve ergonomics and support future scalability. The purpose was not to develop a detailed automated system, but to investigate how automation could influence the design of the powder-logistics concept and whether the proposed configurations could support future automated solutions.

The automation analysis was carried out by reviewing the powder-logistics flow and identifying activities where manual work, transport, lifting or repeated handling could potentially be reduced through automation. This included both internal transport and other powder-handling activities, such as movement between storage, filling, production and powder recovery areas. Possible automated solutions were considered in relation to the identified system constraints, stakeholder input and the practical requirements of handling metal powder in an LPBF environment.

During the study, it became clear that automation could support parts of the logistics system, particularly internal material transport. However, available automation solutions were not considered suitable for fully automating the current powder-handling process without major changes to the way powder is handled. The analysis therefore shifted from full automation towards automation readiness. This meant that the logistics configurations were developed to enable future automation where possible, while still remaining feasible with current technology and manual operation.

Automation readiness was evaluated by considering factors such as clear transport routes, defined pick-up and drop-off points, sufficient space for automated vehicles, standardized load carriers, reduced unnecessary manual movements and separation between transport areas and operator work areas. In this way, automation was treated as a design requirement for future scalability rather than as a complete implementation solution within the scope of the thesis.

2.4.6 Evaluation Workshop

To support the evaluation and refinement of the developed logistics configurations, a second workshop was held with the Company. While the first workshop focused on identifying requirements and generating concept directions, the second workshop focused on validating and evaluating the proposed

alternatives. The purpose was to determine whether the developed configurations were feasible in practice and to identify which design choices should be carried forward into the final concept.

During the workshop, the proposed layout alternatives and key design dimensions were presented to the participants. These included powder-flow logic, storage strategy, unit volumes, internal material handling and the potential role of automation. The alternatives were discussed in relation to the performance dimensions used in the study: efficiency, cost and operational risk. Rather than only comparing numerical scores, the workshop was used to collect stakeholder feedback on practical feasibility, implementation challenges, operational consequences and risks.

A central part of the workshop was to validate the proposed layouts against the actual production environment. Participants discussed whether the layouts could function in practice, whether powder-related activities could be relocated within the workshop, and how the proposed flow would affect daily operations. The workshop also addressed key requirements such as traceability, identification of powder containers, contamination control, manual handling risks, temperature requirements and the possibility of decentralized or cell-based storage.

The output from the workshop was therefore used in two ways. First, it confirmed which logistics configurations were realistic enough to include in the continued performance analysis. Second, it provided qualitative input for the later evaluation of operational risk, investment needs and concept selection. In this way, the workshop functioned as a validation step between concept development and performance analysis, ensuring that the alternatives evaluated in Chapter 7 were not only theoretically developed but also grounded in operational experience from the studied company.

2.5 Performance Analysis

The performance analysis was conducted to evaluate the developed logistic configurations and support the selection of a suitable future concept. This corresponds to the fifth step of the Systematic Layout Planning process, where layout alternatives are evaluated before a final solution (Muther & Hales, 2015). In this study, the evaluation was structured around the three performance dimensions used in the EPL framework, efficiency, cost and operational risk.

Performance measurement is defined as the process of quantifying the efficiency and effectiveness of an action through specific metrics (Gunasekaran & Kobu, 2007). In logistics and supply chain management, performance metrics are important because they support fact-based decision-making and help organizations understand internal processes, identify waste and bottlenecks, and verify improvements. Gunasekaran and Kobu (2007) emphasize this by stating that “no measures, no improvement”. In this study, performance measurement was therefore used as a decision-support tool to compare powder-logistics alternatives and identify the main trade-offs between efficiency, cost, safety, traceability, flexibility and scalability.

The evaluation was based on four main performance indicators, investment cost, material flow efficiency, tied-up capital in powder and operational risk. These indicators were selected because they reflect the main differences between the alternatives developed in the logistics configuration analysis and because they could be evaluated using the available data, stakeholder input and assumptions. Since the study concerns early-stage concept development, the purpose was not to produce exact financial, time-based or quality-based performance values, but to compare the alternatives at a level that supports concept selection.

Time was not used as a separate performance metric. This is because several activities in the future flow are not yet implemented and therefore cannot be timed reliably. In addition, the main efficiency problem identified in the study concerns repeated handling, administration and material movements rather than the duration of individual activities. Time is therefore considered indirectly through the number of activities, transport effort and risk of production interruptions. Quality was not used as a separate performance metric in the analysis. This is because product and powder quality are treated as mandatory requirements rather than optimization criteria. A concept that compromises traceability, contamination

control or powder integrity would not be considered feasible, even if it performed well in terms of cost or efficiency. Quality-related aspects are therefore included indirectly through operational risk, especially through risks such as loss of traceability, cross-contamination, incorrect refill or top-up operations and inconsistent powder quality between builds.

2.5.1 Efficiency Evaluation

Efficiency was assessed using Material Flow Mapping (MFM), consistent with the current-state analysis. The powder-logistics activities were categorized using the HATS framework: Handling, Administration, Transportation and Storage. By comparing the number and type of activities required in each flow, the analysis made it possible to identify differences in logistics complexity and operational workload. This provided a structured basis for comparing how different logistics configurations affect the amount of handling, administration, transportation and storage required in the powder-logistics flow.

2.5.2 Cost Performance and Tied-up capital Evaluation

Internal logistics and material handling represent the processes that enable materials and resources to flow within a company. To manage these operations, organizations use direct performance indicators, which are typically quantitative measures expressed through simple mathematical ratios (Staudt et al., 2015). Cost is a central performance dimension in logistics, since material handling can represent a significant share of total operating cost in industrial environments, while improved layout and handling systems can reduce unnecessary resource use (Staudt et al., 2015).

In this study, cost was evaluated through two indicators, investment cost and tied-up capital in powder. Investment cost was assessed through a simplified planning-level comparison of the equipment and support systems required for the proposed logistics configuration, including storage and identification systems, lifting and handling equipment, and transport alternatives. The purpose was not to produce a detailed procurement calculation, but to identify the main investment differences between the alternatives.

Tied-up capital in powder was evaluated through scenario-based calculations of alternative batch strategies. These calculations estimated how different batch sizes and traceability rules affect powder utilization, remaining powder, waste and the amount of capital tied up in powder inventory. This was included because metal powder is a high-value consumable material and because batch strategy directly affects both financial performance and traceability.

Lower costs indicate a more cost-efficient system where resources are used effectively without unnecessary waste (Staudt et al., 2015). However, logistics performance cannot be evaluated using a single metric, since different system objectives may conflict with each other. In this study, cost performance is therefore considered together with efficiency, operational risk, traceability and scalability.

2.5.3 Operational Risk Evaluation

Operational risk was evaluated using a risk matrix approach, where identified risks were assessed based on probability and impact. The risk analysis was broader than safety alone and included risks related to operator safety, production interruptions, system reliability, flexibility limitations, traceability loss, cross-contamination, implementation complexity and scalability. The risk matrix was therefore used as a semi-quantitative decision-support tool to compare how different layout choices, handling solutions and batch strategies affect the overall robustness of the powder-logistics concept.

Lemmens et al. (2022) describe a risk matrix as a tool used to visually compare different risks. Each risk is assessed based on how likely it is to occur and the severity of its impact if it does occur. The matrix is typically structured as a grid, where probability and impact are rated on a scale of 1–5. For each risk, a risk score is calculated by multiplying probability and impact. For example, if a risk has a probability of 3 and an impact of 4, the resulting risk score is 12. This helps visualize which risks are most critical and require attention. Lemmens et al. (2022) also note that a risk matrix is primarily a

discussion and decision-support tool and should not be relied upon as the sole method for risk management.

Table 2-4. Risk Matrix based on Lemmens et al. (2022).

		Impact				
		Insignificant (1)	Minor (2)	Moderate (3)	Major (4)	Catastrophic (5)
Probability	Almost Certain (5)	5	10	15	20	25
	Likely (4)	4	8	12	16	20
	Possible (3)	3	6	9	12	15
	Unlikely (2)	2	4	6	8	10
	Rare (1)	1	2	3	4	5

2.6 Presentation of respondents

All respondents in this study are employed at the studied company. A total of 14 respondents were interviewed or involved in workshops. Participants were selected using a combination of purposive and snowball sampling. Initial respondents were identified based on their involvement in logistics-related activities, after which additional participants were recommended through ongoing interviews.

The respondents represent a range of roles and departments connected to the powder and logistics, including warehouse operations, production, planning, procurement, and management. They hold positions ranging from operational staff to managerial roles and have varying levels of experience. This diversity provides multiple perspectives on the current setup as well as insights into challenges and opportunities related to the new high-volume shop.

To ensure anonymity, respondents are referred to their role instead of names, an overview of the respondents is presented in Table 2-6.

Table 2-5. Respondents from the studied company.

Respondent	Role	Department	Type of Involvement
1	Purchaser	Purchasing (Powder)	Interview
2	Quality Manufacturing engineer (ME)	Goods receiving	Interview + Environment Workshop
3	SCM Process & tools manager	Logistics	Interview + Environment Workshop

4	SCM Process & tools manager	Logistics	Interview + Environment Workshop
5	Operator	AM (Powder)	Interview
6	Project Manager New Workshop	Sweden Site	Interview + Evaluation Workshop
7	Manufacturing engineer (ME)	AM	Interview + Environment Workshop
8	ME Manager (Supervisor to us from the studied company)	AM	Interview + Environment Workshop + Evaluation Workshop
9	Method owner AM	AM	Interview + Environment Workshop
10	Operator	Thermal coating	Interview
11	Production manager	AM (Powder)	Environment Workshop + Evaluation Workshop
12	Site Environmental Lead	Sweden Site	Environment Workshop
13	Fire and explosion safety	Sweden Site	Environment Workshop
14	Site Operations Director	AM	Interview

The selected respondents were considered particularly relevant due to their direct involvement in the logistics flows and handling of powder, making their insights valuable for both analyzing the current state and identifying improvements for the concept.

2.7 Research Quality

When conducting this study on a powder-logistics concept for a high-volume LPBF production, ensuring high research quality and validity is essential. Esaiasson et al. (2017) emphasize that a central question in research quality is whether a study investigates the phenomenon it claims to examine. In this case, that means accurately capturing the real requirements, constraints and trade-offs that influence the design of a future powder-logistics system. According to Esaiasson et al. (2017), high result validity is achieved through a combination of strong conceptual validity and high reliability. Conceptual validity, as described by Esaiasson et al. (2017), concerns the degree of correspondence between theoretical concepts and the operational indicators used to represent them. In this study, this relates to how abstract concepts such as “scalability”, “automation readiness”, “ergonomic suitability” and “traceability” are translated into concrete and observable indicators. Following the reasoning of Esaiasson et al. (2017), data was collected from multiple functions involved in or affected by powder-logistics, allowing different perspectives on the same phenomena to be captured. This reduces the risk that the study reflects a too narrow or misleading understanding of the problem.

Esaiasson et al. (2017) further describe reliability as the extent to which measurements are consistent and free from random or unsystematic errors. In this study, reliability is therefore closely linked not only to how information about current powder-logistics practices and future needs was documented, but also to how that information was interpreted in the analysis. Since the study is largely based on qualitative

data such as interviews and internal documents, reliability depends on careful documentation and a transparent approach to how empirical material is understood and used.

2.8 Ethical Considerations

Ethical considerations in this study focus on informed and voluntary participation, confidentiality, and careful handling of company-sensitive information. In business research, ethical practice includes obtaining informed consent, protecting participants identities where appropriate, and managing research data responsibly, particularly when it contains information that can be linked to individuals or organizations (Bell et al., 2022).

In this study, interview participants are informed about the purpose of the study, how the information will be used, and that participation is voluntary. Since the thesis will be published by Chalmers University of Technology, participants are also informed that results may become publicly available. To reduce risk, company-sensitive information is treated confidentially and presented at an appropriate level of detail, and participants are offered the option to remain anonymous and to refrain from answering questions they consider sensitive.

3. Theory

This chapter is structured according to the EPL framework and primarily focuses on the Environment (E) and Logistics Configuration (L) dimensions. The chapter is divided into these two areas because the proposed powder-logistics concept is developed based on the relationship between the production environment and the logistics system design. The Environment (E) section includes theories related to contingency theory, system fit, physical constraints, scalability and safety. These theories are included to explain how the surrounding production environment creates requirements and limitations for the powder-logistics system. These factors directly influence how the logistics system can be designed and operated. The purpose of this section is therefore to establish the environmental conditions that the proposed concept must adapt to.

The Logistics Configuration (L) section includes theories related to lean production, bottlenecks, automation, facility layout planning, material handling and traceability systems. These theories are included because they support the development of the actual powder-logistics concept, including layout structure, material flow, transport solutions and storage strategies. The section also includes theories related to automation and operator-support systems such as AGV/AMR-supported transport and Pick-by-Light solutions.

By separating the theory into Environment and Logistics Configuration, the chapter reflects the structure of the EPL framework where the logistics system is designed based on the conditions and requirements created by the production environment.

3.1 Environment - System Constraints and Requirements

This section addresses environmental factors that influence production systems with a focus on how system design must respond to contextual conditions, physical limitations and dynamic environments. It emphasizes key principles such as system fit, flexibility, scalability and safety, which together shape the requirements for effective system configuration

3.1.1 Contingency Theory and System Fit

Nugraha and Soewarno (2024) define contingency theory as the idea that there is no “one-size-fits-all” approach, meaning that no universal system can be applied to every organization regardless of context. According to Nugraha and Soewarno (2024), organizational effectiveness instead depends on contextual factors, such as the environment in which the company operates. Nugraha and Soewarno (2024) argue that organizations must align their structures with specific contingencies to perform optimally and achieve their goals. Furthermore, Nugraha and Soewarno (2024) explain that contingency theory emerged as a response to earlier universalistic approaches, which assumed that there was a single best way to design organizational systems. Nugraha and Soewarno (2024) emphasize that, unlike these earlier perspectives, organizations cannot simply adopt a standardized or “off-the-shelf” structure but must instead adapt their design to fit relevant contingency variables.

Drazin and Van de Ven (1985) states that central to contingency theory is the concept of “fit”, meaning that organizational structure and processes must align with contextual factors such as environment and technology. Drazin and Van de Ven (1985) explains that the system approach further develops this perspective by emphasizing that organizational performance depends on the alignment of multiple interdependent variables rather than isolated factors. Drazin and Van de Ven (1985) mean that design decisions, such as facility layout, must be adapted to a combination of environmental and operational conditions to achieve optimal performance.

3.1.2 Physical and Spatial Constraints

Al-Zubaidi et al. (2021) explain that in environments where the layout is fixed and space is limited, storage areas can easily become a critical bottleneck. Al-Zubaidi et al. (2021) states that since storage capacity is restricted, it can only accommodate a certain volume before reaching its limit. When this capacity is exceeded, the storage area becomes fully occupied, which may interrupt the production flow and, in some cases, force production to stop entirely. To address this issue, Al-Zubaidi et al. (2021)

emphasize the importance of flexibility within the production system. Specifically, they suggest that workstations should be designed to be adaptable to respond to changes in workload and material flow. This can include allowing spaces to serve multiple purposes, such as being used for both powder storage and finished goods when needed. Al-Zubaidi et al. (2021) means that by enabling such flexibility, the manufacturing system can better handle variations in flow and demand, rather than being constrained by fixed storage capacity and risking stoppages due to overflow.

3.1.3 Dynamic Environment and Scalability Requirements

When layouts are subject to frequent changes, Al-Zubaidi et al. (2021) introduce the concept of Reconfigurable Manufacturing Systems (RMS) which is a system designed to be easily modified. According to Al-Zubaidi et al. (2021), the flexibility of a layout should be considered from the very beginning of the design process, considering factors such as varying production volumes or product mix. The system should be built around flexibility and scalability ensuring these attributes are integrated from the outset. Al-Zubaidi et al. (2021) also suggest that layouts should be designed for different time horizons rather than being fixed for the foreseeable future, for example, over 1 year and 2-year horizons. Finally, Al-Zubaidi et al. (2021) emphasize the importance of evaluating the costs associated with rearranging the layout, as these costs impact the overall feasibility of reconfiguring the system.

3.2 Logistics Configuration

This section presents theoretical concepts related to logistics configuration that are relevant for the design of the production system. It covers key areas such as layout planning, lean production principles, bottlenecks, automation and material handling. Together, these concepts describe how internal logistics systems can be structured to achieve efficient material flow, while maintaining flexibility, safety and scalability in dynamic production environments.

3.2.1 Lean production

Lean Production, which has its origin from the automotive company Toyota is explained by Palange and Dhattrak (2021) as a philosophy that is focused on maximizing customer value by minimizing waste in production. The core of lean production is according to Palange and Dhattrak (2021) to identify and eliminate activities that do not add any value for the product being produced. Waste explained by Palange and Dhattrak (2021) come in different forms such as overproduction, waiting times or unnecessary transportation. With this definition Palange and Dhattrak (2021) means that lean is not only about effectiveness but to optimize the whole production system. Palange and Dhattrak (2021) describes different lean manufacturing tools that a company can use, and some are shown in Figure 3-1.

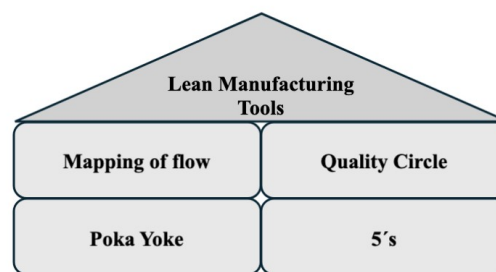


Figure 3-1. Lean Manufacturing Tools based on Palange and Dhattrak (2021).

Palange and Dhattrak (2021) describes mapping of the flow as a method for visualizing the current state of production where both value adding activities and non-value adding activities between process steps are identified and analyzed. Furthermore, Palange and Dhattrak (2021) explains quality circles as a structured brainstorming group in which employees with strong knowledge of the production process collaborate to share ideas and drive improvements. These groups aim to foster a culture of continuous improvements by setting goals, monitoring results and sharing ideas. With active support and involvement from management Palange and Dhattrak (2021) describes that this approach can lead to

increased productivity, improved quality and reduced waste within the production system. Poka-Yoke is described by Palange and Dhattrak (2021) as an “error-proofing” approach, where mechanisms are implemented at critical stages of a process to prevent mistakes before they occur. The aim is to detect or eliminate errors early, thereby reducing the likelihood of defects in the final product. Furthermore, Palange and Dhattrak (2021) defines Poka-Yoke broadly as any mechanism or technique that helps prevent or avoid errors in production.

According to Ramasu, Kanakana-Katumba, Nenzhelele and Mpofu (2025), 5S is a Lean methodology aimed at creating an organized, efficient and safe workplace. The method consists of five principles: Sort, Set in Order (Systemize), Shine (keep it clean), Standardize, and Sustain. By applying these principles, organizations can improve productivity, product quality and the overall work environment. However, Ramasu et al. (2025) mentions that the effectiveness of 5S depends on strong commitment from both operators and management. Furthermore, the 5S strategy also helps visualize problems better making inefficiencies and waste easier to identify and address.

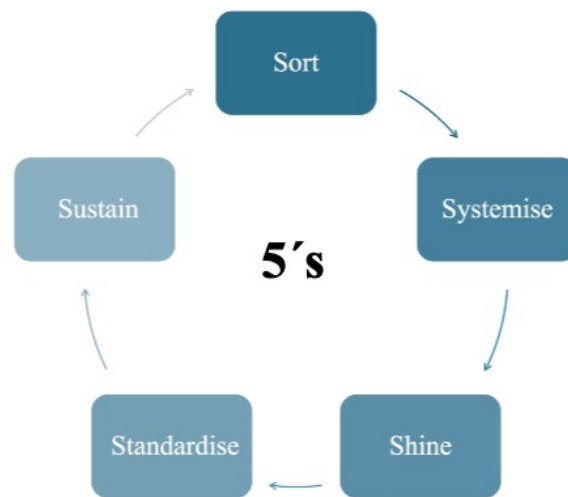


Figure 3-2. 5's based on Ramasu et al. (2025).

3.2.2 Bottlenecks

Tang, Dai, Jiang, Wu, Zhuravkov, Xue and Wang (2024) describe that a bottleneck occurs when the demand placed on a resource exceeds or equals its production capacity, resulting in congestion and limiting the overall system throughput. Tang et al. (2024) also distinguishes between different bottlenecks naming for example machine, human resource and maintenance bottlenecks. According to Tang et al. (2024) the machine with the longest processing time becomes the bottleneck, thereby constraining the overall system throughput. Tang et al. (2024) also mentions the human bottlenecks stating that factors such as workforce availability and skill level can significantly influence system performance and may create bottlenecks if not properly managed.

Furthermore, Tang et al. (2024) highlights that bottlenecks are not static but dynamic, meaning that their location within the system may shift over time as conditions change. This phenomenon is referred to as shifting bottlenecks and reflects the inherent variability in manufacturing systems. To manage bottlenecks, Tang et al. (2024) proposes two main strategies. The first is a proactive approach, where potential bottlenecks are predicted in advance using simulations or historical data, allowing preventive actions to be taken before disruptions occur. The second is a reactive approach, where actions are implemented after a bottleneck has been identified, typically by reallocating resources or adjusting the system to restore balance.

3.2.3 Automation in Logistics

Bernardo et al. (2022) describe the low level of flexibility in internal logistic systems and that there is a need for more flexible methods such as automation. Bernardo et al. (2022) list the many advantages of automating internal logistics which include more scalable operations, continuous real time monitoring of loading operations and performance data, minimization of errors, strengthened organizational control, better customer service and improved process speed. These benefits are further supported by Granlund and Wiktorsson (2014), who emphasize that automation can also lower costs, increase efficiency, and improve the working environment for operators.

Bernardo et al. (2022) explain that the development of artificial intelligence (AI) has significantly increased the flexibility of robotic systems in factory environments. According to Bernardo et al. (2022), production facilities previously had to be physically adapted to accommodate robots. For example, Bernardo et al. (2022) describe how automated guided vehicles required physical infrastructure, such as embedded wires or marked lines on the factory floor, to follow predetermined paths. Furthermore, Bernardo et al. (2022) note that modern robotic systems are now able to navigate using onboard sensors due to advances in AI and robotic perception technologies. This development, as highlighted by Bernardo et al. (2022), reduces the need for structural modifications to the factory layout and allows robots to be integrated more easily into existing production environments.

3.2.4 Layout for Automation

Melo and Corneal (2020) describes three different types of designs for automation layouts which include single-loop, tandem and conventional layouts. According to Melo and Corneal (2020), in a single-loop layout, robots move continuously in one direction along a set path, and the AMR are restricted to this path. Melo and Corneal (2020) explain that this design simplifies control since all robots follow the same path, but it can lead to longer travel distances and a single robot breakdown can halt the entire system.

Melo and Corneal (2020) further describe the tandem layout which divides the area into multiple independent loops, each accommodating one or more robots. Melo and Corneal (2020) note that this design reduces the risk of complete system stoppages, improves robot utilization, and generally performs better in terms of average travel times compared to the single-loop layout.

Melo and Corneal (2020) also explain that the conventional layout offers greater flexibility and can include unidirectional, bidirectional, or hybrid multi-lane configurations. Melo and Corneal (2020) point out that this layout allows AMRs to take shortcuts, minimizing travel time and giving the robots more freedom to calculate optimal routes. Melo and Corneal (2020) emphasize that it is also a robust system, as the AMRs can navigate around obstacles in real time. However, Melo and Corneal (2020) warn that conventional layouts require wider lanes to allow robots to pass each other safely, and the control system must be more sophisticated to manage traffic and prevent collisions. The explained layouts are displayed in Figure 3-3.

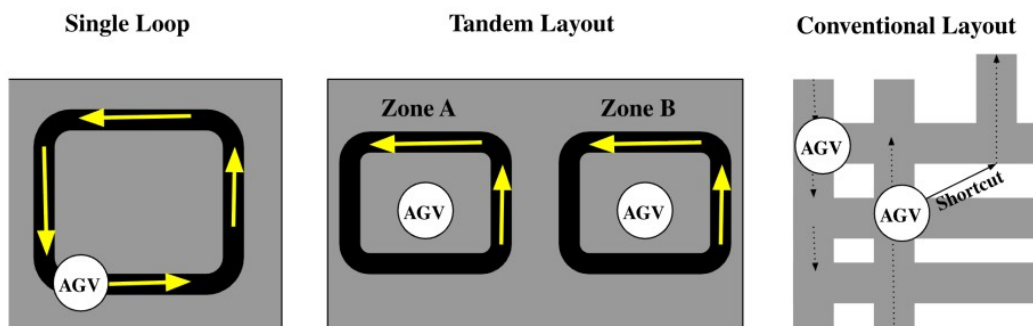


Figure 3-3. AMR Layout designs based on Melo and Corneal (2020).

Melo and Corneal (2020) provide guidance on key factors to consider before selecting an AMR layout. They explain that the width of factory aisles is critical, as narrow passages prevent two robots from passing each other, making tandem and conventional layouts difficult to implement. Another major challenge described by Melo and Corneal (2020) is that production units are often fixed due to technical installations, ventilation systems, or ceiling height. As a result, the layout must be adapted to the existing infrastructure.

To determine the most suitable layout, Melo and Corneal (2020) emphasize the importance of evaluating layouts using specific key performance indicators (KPIs). In their study, they measure factors such as throughput, response time, blockage avoidance, idle time and total costs. Melo and Corneal (2020) also note that choosing the optimal layout involves trade-offs, as it is generally impossible to maximize all KPIs simultaneously.

3.2.5 Facility Layout Planning

Facility layout planning is described by Ramasu et al. (2025) as the process by which a manufacturing company arranges its machines, warehouses and other functions to minimize costs, improve productivity and the material flow. According to Ramasu et al. (2025), an effective layout reduces material handling costs, work-in-process (WIP) and production time. However, Ramasu et al. (2025) highlights a key challenge faced by modern manufacturing systems which is that production volumes and demand can change rapidly leading to shifts in material flow patterns. As a result, a layout that is optimal at one point in time may become less efficient over time, meaning that no single layout remains permanently optimal.

To address this issue, Ramasu et al. (2025) presents two main approaches. The first is a dynamic layout, which adapts to changing demand by optimizing the layout for different time periods. While this approach can improve efficiency, it is often costly and may disrupt production due to the need for frequent rearrangements. The second approach is the robust layout, where a single layout is designed to perform reasonably well over a longer period. Ramasu et al. (2025) explains that although it may not be optimal for any specific situation, it offers greater stability and avoids the disruptions associated with frequent changes and this is the commonly used approach.

Furthermore, Ramasu et al. (2025) identifies five common types of facility layouts: process layout, product layout, cellular layout, fixed-position layout and hybrid layout. These layout types are illustrated in Figure 3-4 except for the hybrid layout.

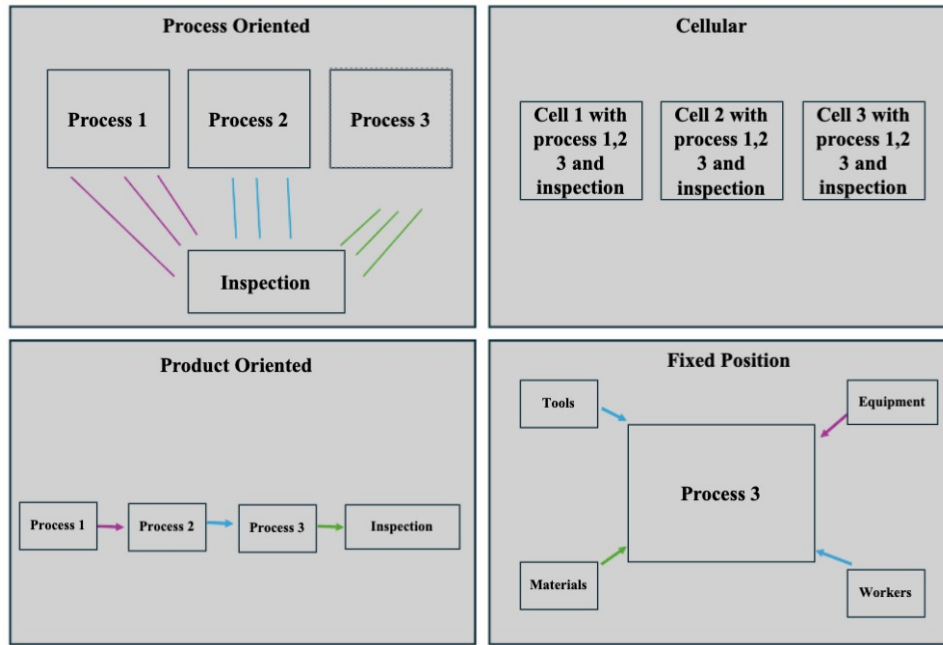


Figure 3-4. Facility Layouts based on Ramasu et al. (2025).

Ramasu et al. (2025) describes the process-oriented layout as a system where work areas are divided into functional zones based on specific tasks. This approach is particularly suitable for companies that handle a wide variety of products or aim to maximize machine utilization. The cellular layout is characterized as “mini factories” where all necessary processes are grouped within a single cell, thereby reducing material movement.

In contrast, Ramasu et al. (2025) describes the product-oriented layout as organized according to the sequence of production steps, allowing the product to move smoothly through each stage. This makes it highly suitable for mass production environments with standardized outputs. The fixed-position layout is most appropriate for large products, such as ships, where it is impractical to move the product and instead materials and workers are brought to the product. Finally, the hybrid layout is described as a combination of elements from both process and product-oriented layouts. While this approach offers flexibility and the potential to leverage the strengths of both systems, it can also result in increased complexity in design and management.

3.2.6 Material Handling

Amjath, Kerbache, Elomri and Smith (2023) define material handling systems (MHS) as the system governing how materials are handled, transported and lifted within factories or warehouses including aspects of both movement and storage. In contrast, material handling equipment (MHE) refers to the physical equipment used to perform these activities such as cranes, trucks and conveyors (Amjath et al., 2023). MHE therefore represents a critical component of the overall system, as it directly determines the efficiency and capability of material flow within a facility. Amjath et al. (2023) divide the MHS into three different types which include conveyors, cranes/hoists and transporters. The selection of a material handling system can according to Amjath et al. (2023) be divided into two main categories, design-related and operational features. Design features include decisions related to fleet size, material flow routing, unit load definition and dispatching policies all of which influence the structure and configuration of the system. Operational features on the other hand focus on how the system is managed in practice, primarily through scheduling and maintenance activities. Together, these factors determine the overall performance and suitability of the selected MHS. These are displayed in Figure 3-5.

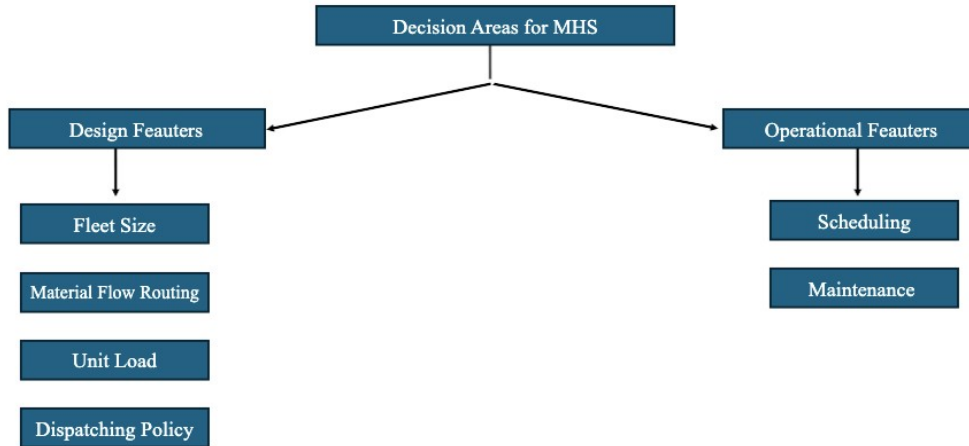


Figure 3-5. Decision Areas for MHS based on Amjath et al. (2023).

3.2.7 Layout for Material Handling

According to Drira, Pierreval, and Hajri-Gabouj (2007) material handling systems and facility layout design are strongly interdependent. Drira et al. (2007) mean that decisions regarding the arrangement of machines directly influence the feasible choice of material handling systems, while the selection of handling equipment in turn constrains how the layout should be structured. Due to this interdependency and the complexity of solving both problems simultaneously, they are typically addressed sequentially in practice to achieve a feasible and well-aligned system design.

Drira et al. (2007) further describes several standard layout configurations that can be adopted depending on how machines and workstations are arranged within the facility. Figure 3-6 illustrates the single-row layout, where equipment is placed in a linear sequence and material flows sequentially between stations along the line.

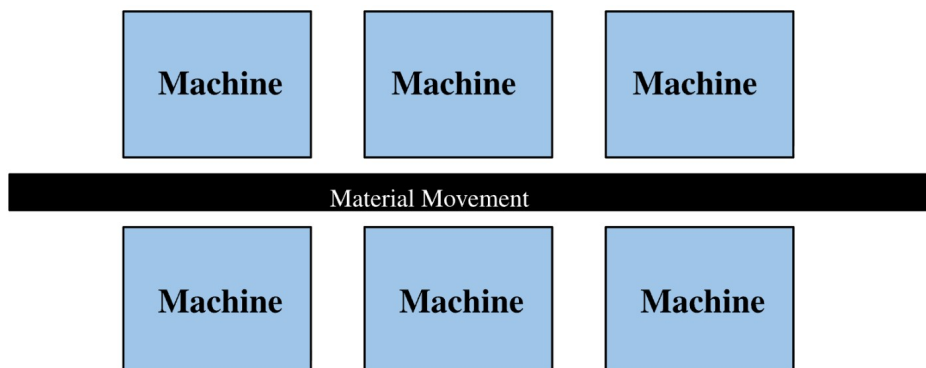


Figure 3-6. Single Row Layout based on Drira et al. (2007).

Drira et al. (2007) explains that, in an ideal production layout, material should move sequentially through the system following a predefined flow. However, the concept of “backtracking” is introduced, as illustrated in Figure 3-7, to describe situations where material movement deviates from this intended sequence.

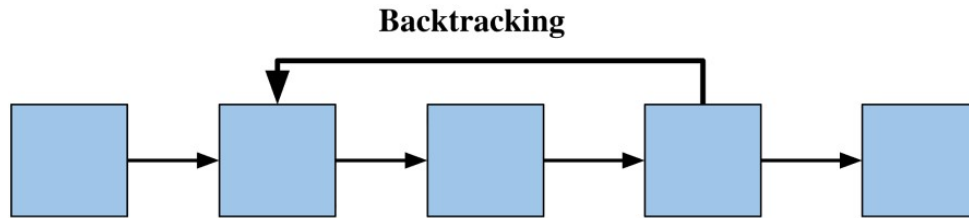


Figure 3-7. Backtracking based on Drira et al. (2007).

Backtracking occurs when material moves against the logical process flow, for example following the sequence $A \rightarrow B \rightarrow D \rightarrow C$ instead of the intended $A \rightarrow B \rightarrow C \rightarrow D$. This disrupts the flow structure, increases transportation distances, and can create inefficiencies in the production system (Drira et al., 2007). Therefore, the layout must be carefully designed to ensure a consistent and forward-oriented material flow, minimizing the occurrence of backtracking within the system.

3.2.8 Batch Separation

Holah (2011) describes how effective batch separation and the prevention of cross-contamination can be achieved through multiple levels of protection. The first level is the production site, which acts as a barrier against external risks such as traffic and environmental factors. The second level is the factory building, which prevents dust and other external contaminants from entering the production environment. The third level consists of high-risk or high-hygiene zones, where strict controls and high cleanliness standards are maintained. The fourth level is the product enclosure, such as closed systems within machinery, where the environment is highly controlled.

Holah (2011) explains that each level reduces the risk of cross-contamination, with increasing levels of control closer to the product. Furthermore, material separation can be achieved through controlled flow design, where clean materials enter from one side of the facility and waste or contaminated materials exit through another, ensuring that flows do not intersect. This is demonstrated in Figure 3-8. These flows must be clearly separated. Holah (2011) also describes the concept of a “box within a box,” where sensitive materials are completely isolated from the surrounding environment, for example in a separate room. In addition, tools and equipment can be color-coded to further support clear separation between materials.

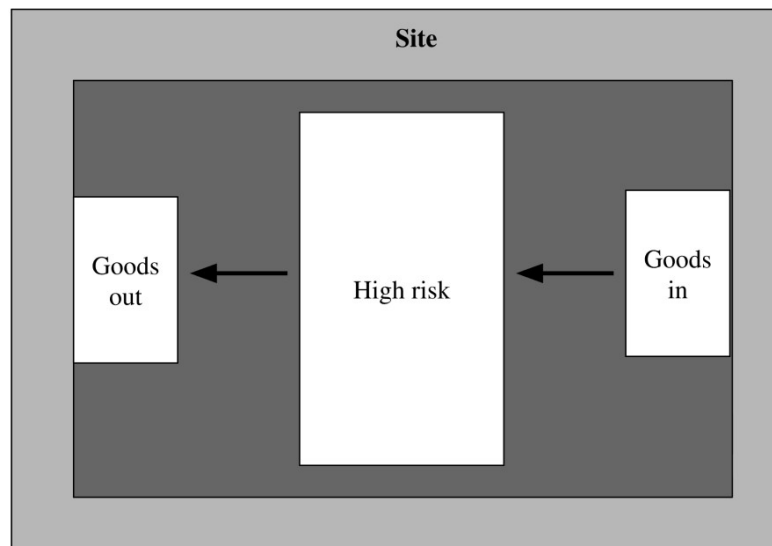


Figure 3-8. Layout designs for batch separation based on Holah (2011).

3.2.9 Picking Information Systems

Trojanowska, Husár, Hrehova och Knapčíková (2023) describes the concept of Poka Yoke, a Japanese term for error prevention which is widely used in modern production systems to improve efficiency by minimizing human errors. One approach to achieving this is by simplifying the operator's task so that the correct action becomes the most intuitive one.

According to Battini, Calzavara, Persona and Sgarbossa (2015), several technology-based order picking systems have replaced traditional paper-based picking methods in modern warehouses. These include voice picking systems, pick-by-light systems, RFID-based pick-by-light solutions as well as handheld technologies such as barcode and RFID scanners.

These technologies are described by Battini et al. (2015) designed to support operators by providing real-time guidance regarding both product information and storage locations. In voice picking systems, operators receive instructions through a headset and confirm completed picks verbally via a microphone, enabling a hands-free working process (Battini et al., 2015). In contrast, Trojanowska et al. (2023) explains that pick-by-light systems use visual indicators, typically LED lights, to guide operators to the correct storage location. When an item is required, the corresponding location is illuminated, clearly indicating where the operator should pick. Figure 3-9 illustrates an example of this type of system.

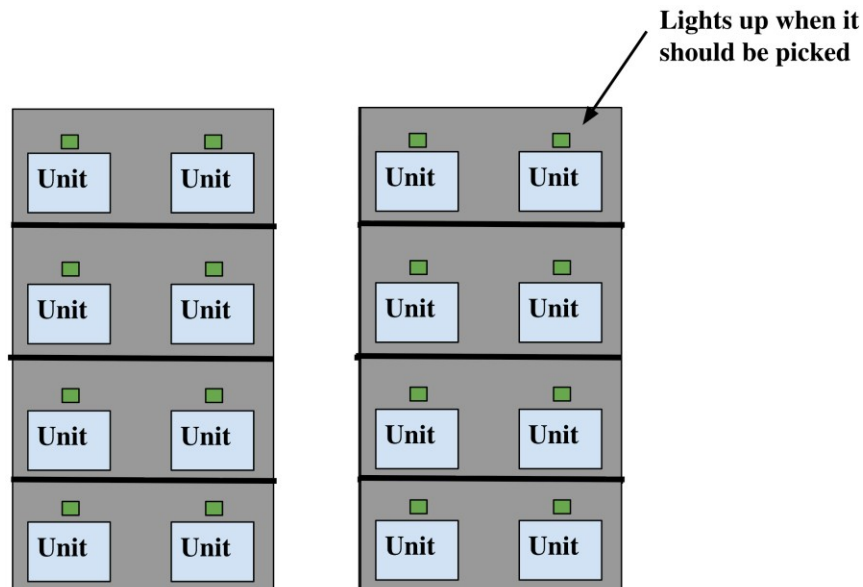


Figure 3-9. "Pick-by-Light" System based on Trojanowska et al. (2023).

In many implementations, Trojanowska et al. (2023) explain that operators are also required to confirm the pick by pressing a button or similar device, adding an additional layer of error prevention in case of incorrect actions. The combination of visual guidance and manual confirmation helps reduce the risk of human error in the picking process.

A further development of this concept is RFID-based pick-by-light systems explained by Battini et al. (2015) as where the operator may use an RFID-enabled glove or device. This allows the system to automatically register the pick, as the action is detected without requiring manual confirmation from the operator.

3.2.10 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is described by Schmidt, Thoroer and Schumann (2013) as a technology used to automatically identify and track objects using radio waves. Unlike barcode systems, RFID does not require a direct line of sight, meaning that tags can be read automatically and multiple

objects can be identified simultaneously. In industrial environments, RFID is often used to track materials, containers or products throughout production and logistics flows. Schmidt et al. (2013) explains that the system consists of tags attached to objects while readers can be placed on handheld devices or gates and connected to digital systems for tracking and information handling. According to Schmidt et al. (2013), RFID can improve traceability, reduce manual work and increase efficiency by automating the registration of material movements. In many cases, RFID is used together with barcode systems to improve reliability and compatibility.

4. Empirical data

The purpose of this chapter is to present the empirical data collected through interviews, observations of current powder handling, and workshops conducted at the studied company. The results are structured by first describing the respondents, followed by an overview of the environmental requirements and constraints that cannot be influenced and form the fixed conditions of the system. This is followed by a presentation of the design (logistics configuration) data, including the current state of operations as well as suggested process configurations, material handling, automation options, and layout structures identified during the workshops.

4.1 Environment

This section outlines the fixed environmental constraints that establish the operational boundaries for the logistics configuration. It is divided into four sub-sections, physical environment, inbound logistics, system and operational constraints, and material and traceability requirements.

4.1.1 Physical Environment

The future powder logistics environment is characterized by a high degree of uncertainty regarding the final facility layout. As the Project Manager explained:

“No final decisions have been made on layout. The different layouts presented should be seen as possible options, not finalized solutions. Top management has not yet decided on the final layout or strategy.”

– Project Manager

This indicates that the environment in which the system will operate is not fixed, and that both spatial conditions and process configurations remain subject to change depending on strategic decisions made by management.

The current layout proposals indicate that powder handling activities, such as the “Powder hopper filling” area, will be assigned designated spaces within the facility. Furthermore, powder storage is required to be in a separate building, creating a physical separation between storage and production environments. The production system is expected to follow a cell-based structure, where each cell supports four machines. This structure is intended to be repeatable, allowing the facility to scale by duplicating cells as capacity requirements increase.

While the facility layout remains flexible, the machines themselves are largely fixed due to the high cost of modifications. As the Project Manager emphasized:

“AM equipment modifications are very expensive, so the layout must be carefully planned from the beginning.”

– Project Manager

This introduces a critical constraint on the environment, although room arrangements and process flows can adapt, the positioning of machines forms a fixed backbone around which all other processes and transport routes must be designed. Consequently, the future environment requires that any powder logistics concept can accommodate both the uncertainty in spatial layout and the fixed nature of the machines, while maintaining operational efficiency and safety.

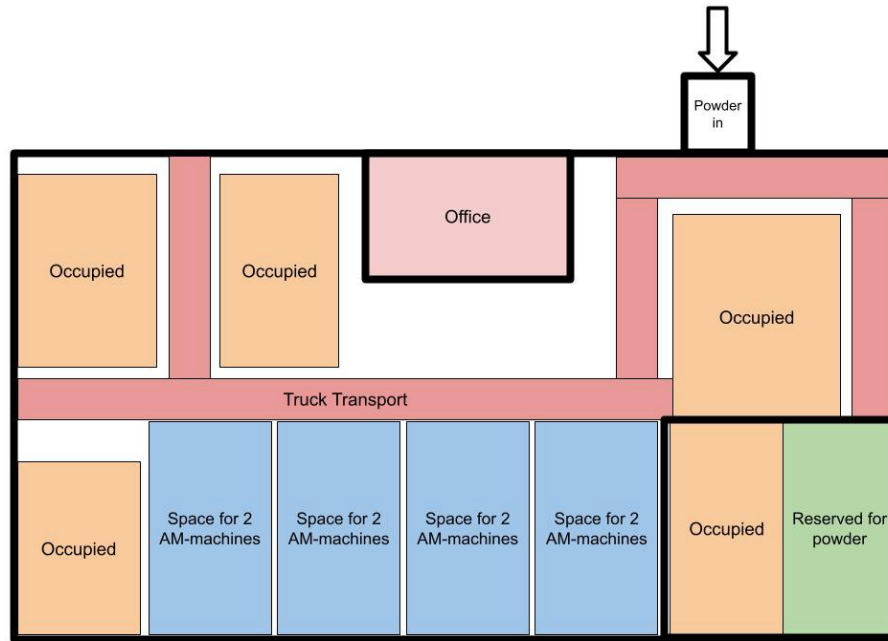


Figure 4-1. Layout Proposal from the studied company.

The original concept assumes a greenfield solution with approximately 200 m² available, see green area in Figure 4-1, while at the same time aiming to avoid major modifications to the existing production facility. These conditions define important spatial and structural constraints for the future environment.

4.1.2 Inbound Logistics Constraints

The goods receiving environment is characterized by several external constraints. Delivery volumes can be large, with shipments of up to several tons that must be handled simultaneously, particularly when powder is delivered in small containers. In addition, each container must be labeled twice, which further complicates the receiving process as this task is performed manually. This increases both the time required and the workload for operators. Powder is not classified as dangerous goods for transport, meaning that the primary constraint is instead the loading capacity of the trucks, which is approximately 32–40 tons. Additionally, current workflows rely heavily on paper-based systems, indicating limitations in digital system support.

4.1.3 System and Operations constraints

The empirical data highlights a strong need for a flexible and scalable system design, primarily driven by uncertainty in future production volumes and the lack of finalized layout decisions. This implies that any proposed concept must be adaptable rather than fixed. This uncertainty is further reinforced by the fact that production volume is currently based on assumptions, making it difficult to dimension a system for a stable, long-term state. In addition to this, the concept of modular production setup has been emphasized by the project manager:

“A cell structure supporting four machines could be designed”

– Project Manager

A cell structure supporting four machines per cell has been proposed, allowing the layout to be duplicated if production capacity increases. This flexible approach ensures that production can adapt to future growth without requiring major facility modifications

The empirical data highlights several critical design requirements for the logistics system to ensure efficient, reliable and flexible handling of both incoming powder deliveries and internal transport. A key requirement is timely and predictable delivery management, as the current process is largely reactive, with orders often placed on short notice, complicating planning and scheduling. Consequently, design requirements emphasize improved scheduling, coordinated transport management and the ability to accommodate larger or variable delivery volumes, while maintaining accuracy in verification, labeling, and documentation.

Several operational design constraints need to be considered in the design. For instance, it is explicitly stated that:

“Interfaces between powder activities should not be physically interconnected, like a conveyor belt” and that “no fixed pipes should directly feed powder into the machines”

– Project Manager

This restricts the use of centralized or highly integrated solutions and instead pushes the design toward decentralized and independent units. Additionally, economic constraints play a significant role, as:

“SLM equipment modifications are very expensive”

– Project Manager

Meaning that the logistic configuration must minimize the need for changes to existing equipment. Overall, the empirical findings suggest that flexibility should not only be achieved through scalability in capacity, but also through independence between system components and minimal reliance on fixed infrastructure.

4.1.4 Material and Traceability Requirements

Traceability and material management constitute critical requirements for the powder logistics system. The empirical data shows that powder usage and batches must be tracked across all cells to ensure safe and consistent production, particularly in a scalable production environment. As highlighted:

“It is important to verify powder traceability”

– Project Manager

In addition, waste powder generated during operations, particularly from the de-powdering station (DPS), must be strictly controlled to prevent it from re-entering the machines:

“Waste powder must be monitored to ensure it does not re-enter the machines”

– Project Manager

A further requirement is that different powder types must not be mixed during handling, due to both safety risks and product quality requirements. The current use of color coding and separate funnels illustrates the necessity of maintaining strict material separation. Moreover, the system environment requires reliable monitoring and tracking of powder flow and usage. This includes maintaining batch separation, ensuring full traceability, and supporting accurate documentation to meet safety and regulatory requirements.

Overall, these conditions define essential requirements on the system, requiring strict traceability, controlled material handling, and continuous monitoring of powder throughout the entire process.

While the facility layout remains flexible, the machines themselves are largely fixed due to the high cost of modifications. As the Project Manager emphasized:

“SLM equipment modifications are very expensive, so the layout must be carefully planned from the beginning.”

– Project Manager

4.2 Current Logistic Configuration

The current powder logistics process is illustrated in Figure 4-2. The process begins with powder arriving at the goods receiving area, followed by storage and transport to the workshop. The powder is then manually filled into machine tanks through a multi-step process. After production, excess powder is recovered at the de-powdering station (DPS) and returned to storage for reuse.

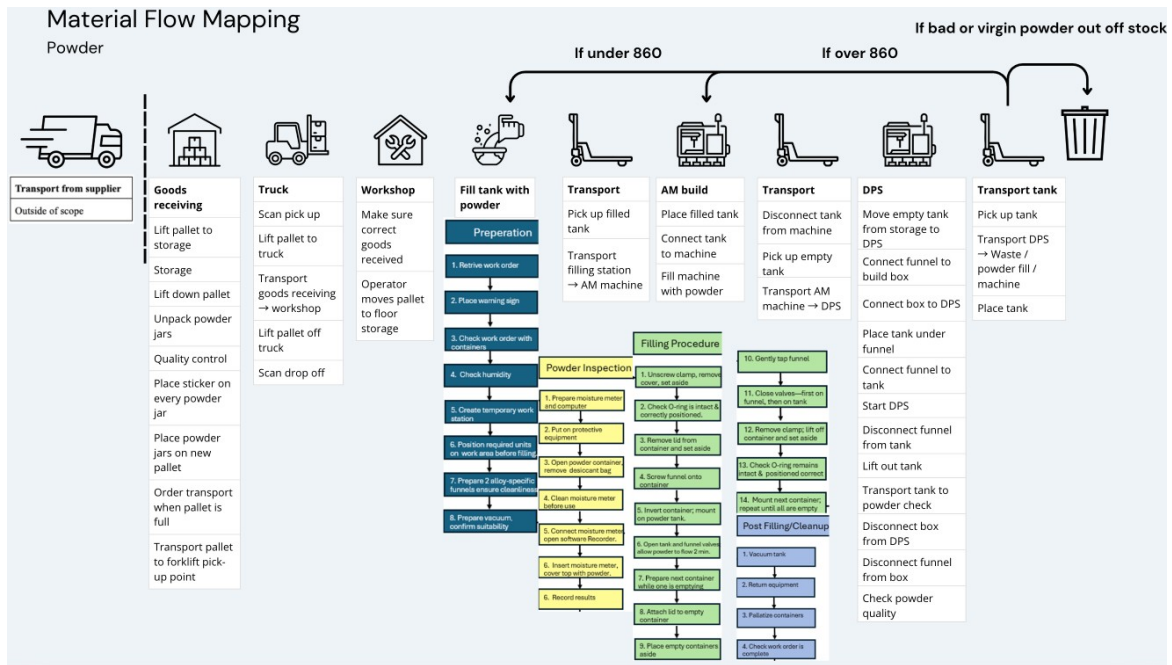


Figure 4-2. Material Flow Mapping for powder flow today.

Throughout the process, several challenges can be identified, including manual handling, lack of dedicated storage areas, and time-consuming filling operations. These issues are further analyzed in the following sections.

4.2.1 Current State Purchasing

The predictability of powder supply represents a major challenge for production planning. Interviews with the purchasing department indicate that procurement is largely reactive, with no formal forecasting system or defined reorder points. Orders are typically triggered by immediate production needs and are often placed at short notice.

“At the moment, purchases are made only based on specific orders, often arriving late and expected to be available the next day.”

– Purchaser

Lead times for powder deliveries vary significantly, ranging from two weeks to up to four months, which adds substantial uncertainty to the already reactive ordering process. This variability, combined with limited storage capacity for pallets and containers, restricts the ability to buffer against delays or manage large incoming shipments.

“Currently all orders are made spontaneously without forecast or reorder points.”

– Purchaser

This creates significant uncertainty in the supply process and makes production planning difficult. Furthermore, limited system support and a lack of reliable consumption data make it difficult to establish accurate forecasts, reinforcing the dependence on reactive procurement

4.2.2 Current state goods receiving

The next step in the powder supply chain is the goods receiving department, where all incoming powder deliveries are carefully inspected. The process includes declaration, verification of quantity and documentation, and comparison of the powder specifications with supplier certificates. It should be noted that declaration is only required for powder imported from outside the EU. Each package is then labeled with two stickers manually which can be very time consuming, indicating both hazardous material and batch information. Once the inspection and labeling are completed, the powder is transported to the AM workshop for production. The total goods receiving process typically takes about one week, although it can vary depending on shipment size and warehouse workload.

“Every shipment is checked carefully against the documentation and certificates before it can be moved to the production floor”

– Quality ME Goods Receiving

Figure 4-3 provides a detailed overview of the goods receiving process.

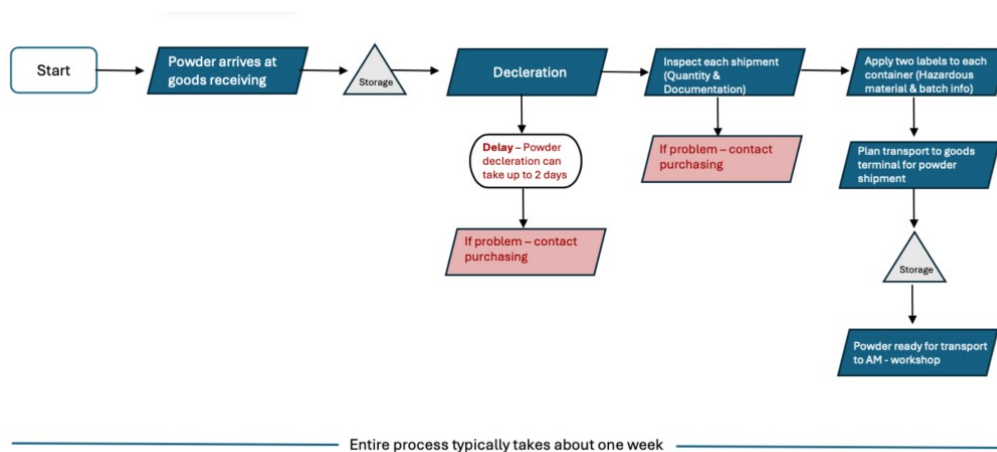


Figure 4-3. Goods Receiving Process.

The empirical findings indicate that the goods receiving team is particularly concerned about potential changes in powder delivery volumes. Currently, much of the work in the goods receipt process is manual, including the placement of labels on each container.

“We have to put two labels on each container manually, one for hazardous goods and one with batch number”

– Quality ME Goods Receiving

An increase in delivery volumes would therefore have a significant impact on the workload and efficiency of the goods receiving process. In addition, the internal transport of powder from the goods receipt area to the AM workshop is performed manually, adding further complexity and workload to the process.

4.2.3 Current state Transport & Workshop

After passing through goods reception, a transport order is manually created for the powder. A truck then collects the pallet from the reception building, scanning it to verify that the correct pallet has been selected, before transporting it to the workshop. The titanium powder is moved to an external storage container located outside the building, and the Inconel powder is transported directly to its designated storage location on the shop floor, see Figure 4-4. Upon arrival, the truck driver performs an additional manual scan to confirm delivery at the correct location. Finally, the responsible personnel verify manually that the correct goods have been received and stored appropriately.

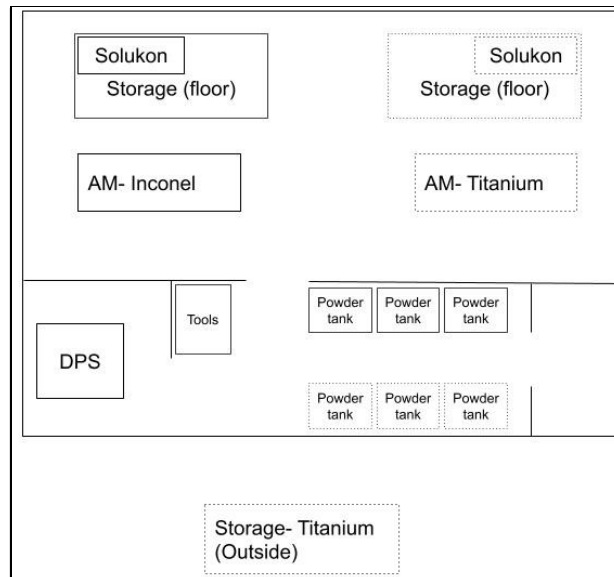


Figure 4-4. Overview of the powder workshop today, dotted lines for titanium.

Once the powder has been internally transported to the AM workshop, it is handled within a carefully controlled production environment. Due to safety considerations, titanium powder is stored outside the main facility. Consequently, smaller containers are manually transported into the shop floor storage area one at a time. Only the quantity required for the next filling operation is brought inside, allowing the material to acclimate to the controlled environment for a specified period prior to use.

A color-coding system is implemented throughout the workshop to prevent cross-contamination between the two materials. The only equipment shared between materials is the de-powdering station (DPS), which is used to remove and recover loose powder by directing it back into the powder containers. To ensure material separation, dedicated funnels are used for each material, thereby preventing any risk of mixing. In addition, storage areas are clearly delineated with marked lines on the floor.

As illustrated in Figure 4-4, the current powder workshop is equipped with two AM machines, each dedicated to a specific material, one for Inconel 718 and one for titanium. Following the de-powdering process, Solukon systems are used to remove residual powder that could not be dislodged in the DPS, by applying pressurized argon gas to the printed components. Every transport between each station is done manually by the operator either by hand or with a powered stacker truck.

4.2.4 Current state Powder filling

The filling process begins with careful preparations and checks to ensure safety, quality, and traceability. First, the work order, equipment and environmental conditions are verified, followed by an inspection of the powder, where moisture content is measured and documented. The actual filling is then carried out using a structured method in which containers are connected, emptied and replaced in a controlled

sequence. Finally, the process concludes with cleaning, equipment restoration and verification that all work has been properly completed. The full process is displayed in Figure 4-5.

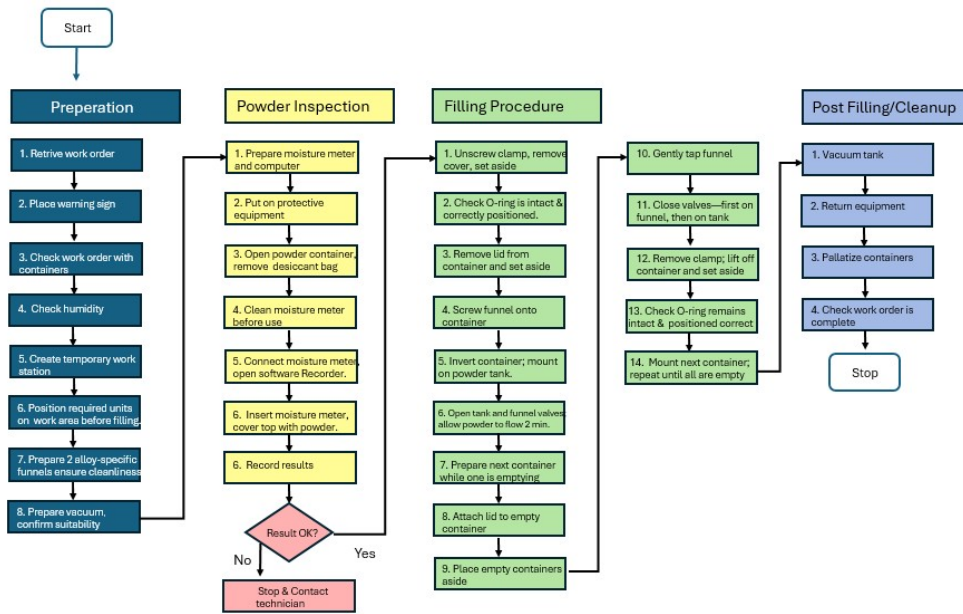


Figure 4-5. The full process of filling powder from the 5L containers into the large powder tanks for an operator.

From an operational perspective, operators experience challenges with ergonomics and time consumption when filling powders.

“Filling powders is heavy and takes a lot of time”

– Operator, Powder

Empirical data highlights material handling as a key area for improvement, with several design requirements emerging to ensure a more efficient and safer workflow. The current process is highly manual and labor-intensive, particularly for heavy powders such as Inconel 718. Managing multiple machines simultaneously further complicates the task. Current equipment, such as plastic powder funnels, is not sufficiently durable for these heavy powders, often breaking during use and creating additional work for operators. This highlights a critical need for more robust, ergonomically designed solutions that reduce physical strain while maintaining accuracy and safety. In addition, there is a clear wish for the research to investigate how the future workshop can be designed with automation in mind, either through the implementation of partially automated handling systems or by ensuring that processes and equipment are compatible with future automation upgrades.

A separate department works with powders for thermal spraying, which is a coating process. Certain parts of the logistics for this department are outsourced, but the general challenges with powder handling, safety, and traceability are like those observed in the AM workshop, including extensive manual powder handling and other labor-intensive steps. Overall, the current state highlights multiple operational, logistical, and ergonomic challenges, as well as limitations in system support, further reinforcing the importance of scalable and automation-ready solutions.

4.2.5 Powder Loop

After a new powder batch is introduced into production, it enters a reuse cycle consisting of non-melted powder. Once a build is completed, only approximately 20% of the powder is melted. The remaining 80% is collected from the build chamber and transferred back into a SLM tank in the DPS. This used powder is stored until the machine is ready to be refilled.

Today, there is no established limit on how many reuses a powder batch can undergo. As a result, the powder is analyzed after the DPS to determine whether it remains suitable for production or must be discarded as waste. An illustration of the powder reuse loop is shown in Figure 4-6.

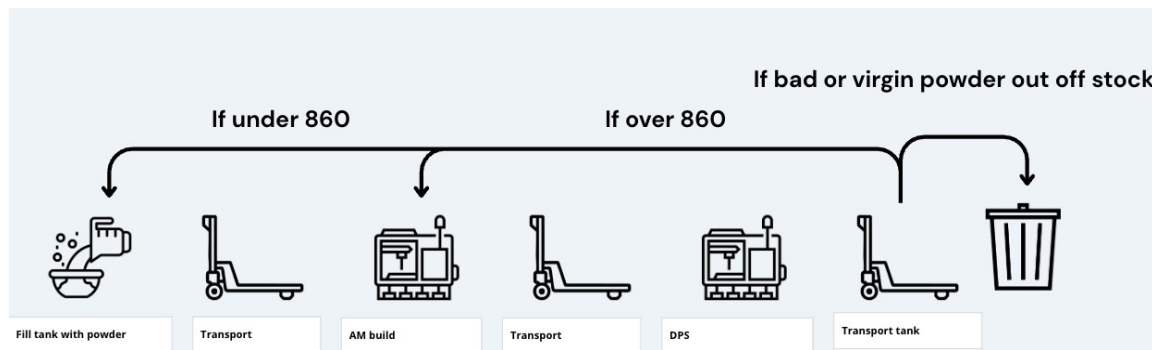


Figure 4-6. Powder reuse loop.

4.3 Environmental Workshop

This section presents the findings from the logistic configuration workshop in which participants defined key requirements for the future production system for powder handling. Topics included layout design, material flow, safety, automation, and cost assumptions. The outcome provided input for the conceptual system design and key parameters used in the analysis.

4.3.1 Storage Strategy

The current production setup is structured around systems where two powder tanks are dedicated to a single machine, while a De-Powdering Station (DPS) is shared among multiple systems. In the planned factory, each machine is expected to consume approximately 200 kg of powder per week.

A key principle identified during the workshop is that each batch should be dedicated to a single machine and not shared across multiple machines. Consequently, inventory cannot be managed solely based on total volume but must instead be controlled at the batch level. Even if powder is physically available in storage, it may already be allocated to a specific machine and therefore unavailable for others. To ensure production continuity, a buffer corresponding to 1–2 additional batches should be maintained, allowing rapid allocation in cases of delayed deliveries, quality deviations, or changes in production priorities.

Another critical aspect is maintaining full traceability and clear separation between different powder categories. These include virgin powder and by-products (i.e., powder that can no longer be reused). Each category follows a distinct material flow and must be physically separated to minimize the risk of contamination or incorrect usage. One example brought up was through clearly defined zones within the layout, for example by using walls or other physical barriers.

Powder should be stored in dedicated, controlled environments rather than in external containers. Prior to use in production, the powder must be acclimatized for at least 24 hours under controlled temperature conditions. To optimize both safety and logistics, the goods receiving area and climate-controlled zone should be integrated within or directly to the production facility. This reduces internal transportation requirements and simplifies fire safety management, as fewer separate storage locations need to meet safety regulations. If receiving goods is in a separate building, rapid and controlled transport to the production area becomes necessary, since powder should not be stored outside the workshop environment.

Furthermore, it was noted that powder deliveries must be made directly into the production facility through a controlled entry point, such as a designated gate. This is due to regulatory requirements that restrict handling of metal powder in open environments.

In summary, the layout should be designed with the requirements of powder handling as the primary driver, rather than adapting powder management to an existing facility structure. This implies adopting a “blank sheet” approach, where material properties, safety requirements and process flows dictate the overall design of the production system.

4.3.2 Safety

Experimental testing indicates that Inconel powder is not classified as highly flammable. However, as a precautionary measure, storage areas containing metal powder should be designed with appropriate fire protection to safeguard both materials and production processes, as well as to prevent the spread of fire within the facility. One approach discussed during the workshop is the use of fire-resistant segmentation. By dividing the production area into separate, fire-protected cells the potential impact of a fire can be limited to a confined zone, thereby reducing the risk of damage to multiple machines and large volumes of powder. Nevertheless, it was emphasized that such fireproofing solutions can be costly. Given that Inconel poses a lower fire risk compared to more reactive materials such as titanium, the extent of fireproofing should be carefully evaluated in relation to cost and actual risk levels.

In the context of automation, no significant safety concerns were identified regarding the operation of battery-powered systems, such as automated guided vehicles (AGVs), in proximity to metal powder. However, charging stations represent a higher risk and therefore require special consideration. These stations should be in dedicated, segregated areas, ideally within fire-resistant enclosures. This ensures that, in the event of a fire originating from a charging station the risk of spread to powder storage or production areas is minimized.

4.3.3 Filling Point

Relocating the filling point to external suppliers, for example by sending tanks to be filled off-site, was discussed during the workshop but considered impractical. A primary concern is the increased risk of contamination associated with external handling. Containers may be exposed to uncontrolled environments during transportation such as airports before being reintroduced into controlled production areas, which compromises cleanliness requirements.

In addition, the containers themselves are costly, further reducing the feasibility of such an approach. Overall, the workshop participants concluded that externalizing the filling process would introduce unnecessary complexity and risk into the system. However, buying or making other tanks that are not “original SLM” tanks was suggested as a solution to have separate tanks for transports outside of the workshop.

4.3.4 Volume Units

Currently, powder is commonly delivered in 10 kg containers which can be considered a widely used standard. However, both suppliers and machine manufacturers (e.g., SLM) are exploring alternative packaging solutions, resulting in a lack of standardization across the industry. This raises important questions regarding system compatibility, such as whether different container types would require unique interfaces or handling systems. The need for industry-wide development in powder packaging was emphasized, as the current situation creates inefficiencies and complicates automation efforts.

From a regulatory perspective, containers exceeding 25 kg require the use of lifting aids. However, workshop participants noted that such aids are often perceived as complex, time-consuming and difficult to use, leading operators to avoid them when possible. To ensure compliance, it was suggested that containers should be designed with sufficient weight to discourage manual lifting altogether, thereby enforcing the use of lifting equipment.

Safety risks related to container weight were also highlighted. While dropping a 10 kg container may not necessarily result in injury, significantly heavier containers (e.g., 100 kg) pose a substantial risk and are likely to cause serious harm. This trade-off between ergonomics and safety must therefore be

carefully considered in container design. Furthermore, the current container design was described as inefficient and unsuitable for automation. The process of manually unscrewing lids and cleaning interfaces introduces additional handling steps and increases the risk of contamination, making it difficult to integrate into automated systems.

Finally, flexibility in supplier relationships was identified as an important constraint. The studied company wants to source powder from at least two suppliers. As a result, any proposed solution must be compatible with multiple container types and supplier-specific variations.

4.3.5 Automation

During the workshop, automation was primarily discussed in relation to reducing manual handling of metal powder. “Automation” in this context refers to the use of AGVs (Automated Guided Vehicles).

Automation is largely motivated by health concerns, as exposure to powder may pose risks to operators. Consequently, tasks involving direct interaction with powder such as opening containers, filling machines, accessing the build chamber and operating the De-Powdering Station (DPS) were identified as key candidates for automation or elimination through closed handling systems.

In addition to improving safety, automation was also highlighted to increase operational efficiency and robustness. Current practices involving manual inventory management, such as tracking with pen and paper, were identified as insufficient for a high-volume production environment. Instead, inventory monitoring should be digitalized and integrated with a Manufacturing Execution System (MES), enabling real-time tracking of material levels and improved coordination with production planning.

Workforce-related challenges further reinforce the need for automation. The workshop participants noted a limited availability of operators, making production highly sensitive to disruptions such as unplanned absence. Due to regulations an operator is not allowed to work by themselves which means that if one operator is absent it may lead to a complete halt in production. Moreover, operators are currently exposed to powder across multiple process steps, increasing both health risks and dependency on manual labor.

4.3.6 Additional Information

The operator hourly cost is estimated at approximately 1500 SEK/h, including both direct and indirect labor-related costs. This value can be considered an assumption used for cost calculations where full cost coverage is required. For comparison, a target or commonly referenced cost level is around 1000 SEK/h, which may represent a more efficient or long-term optimized operational cost depending on the production setup and resource utilization. In addition, the powder material cost is set to 75 EUR per kg, which is used as a key input parameter in the overall cost calculations for the process.

5. Key Environmental Constraints

This chapter presents the analysis of how the empirical findings relate to relevant theoretical frameworks. It focuses on how environmental and operational constraints shape the design of the logistics system and how these factors influence key decisions regarding layout, automation, flexibility and safety. The environmental part is illustrated in the EPL framework in Figure 5-1.

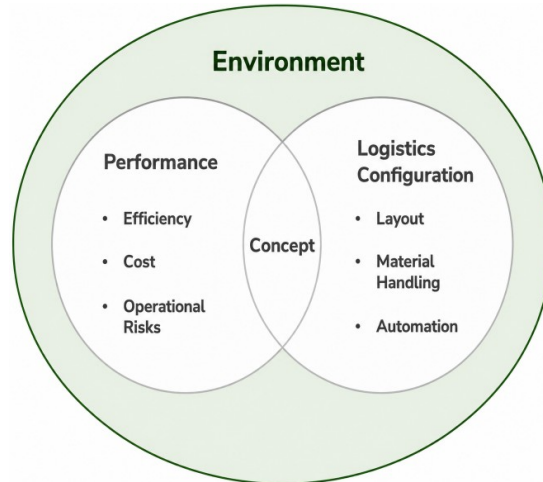


Figure 5-1. EPL Framework, Environment highlighted.

The production environment at the studied company is characterized by several structural and regulatory constraints that define the operational boundaries of the system.

The empirical findings from the workshops and interviews strongly support the principles of contingency theory, which emphasize that system design must be adapted to contextual conditions rather than following a universal solution (Nugraha & Soewarno, 2024). In this case, the logistics configuration is shaped by a combination of environmental uncertainty, physical constraints, safety regulations and operational requirements. This confirms that a “one-size-fits-all” approach such as fully automated or highly standardized systems is not feasible in this context.

The concept of “fit,” as described by Drazin and Van de Ven (1985), is particularly clear in the empirical data as the proposed concept must align with both environmental and operational factors. The future production system is not fully defined and is therefore characterized by uncertainty in layout decisions, while still including fixed elements such as machine positions. In addition, powder handling risks impose strict requirements on material flow, equipment selection and separation of processes.

From an operational perspective, several key requirements were identified. The system must ensure full traceability of powder batches, maintain strict separation between different material types and support controlled and predictable material flows. Furthermore, the need for flexibility and scalability was emphasized, as production volumes are uncertain and expected to change over time. This aligns with the concept of Reconfigurable Manufacturing Systems (RMS) presented by Al-Zubaidi et al. (2021), where systems are designed to be easily modified in response to changing conditions. In this context, flexibility must be embedded from the early design stage, allowing the system to handle variations in production volume and product mix. Rather than designing for a fixed end-state, the layout should support different time horizons and enable gradual adjustments as requirements evolve. Al-Zubaidi et al. (2021) also emphasize that systems need to be flexible, allowing spaces to serve multiple purposes and adapt to changes in flow and demand which further reinforces the need for a dynamic layout. However, Al-Zubaidi et al. (2021) mentions that increasing flexibility also introduces trade-offs, as frequent layout changes may involve significant costs and operational disruptions. Therefore, the system

must balance reconfigurability with stability, ensuring that adjustments are feasible while still maintaining efficient and reliable operations.

Physical and spatial constraints further reinforce this alignment. As highlighted by Al-Zubaidi et al. (2021), limited space and fixed layouts can create bottlenecks and restrict system design. This is reflected in the empirical findings, where machine positions are largely fixed and storage must be carefully integrated into the production environment.

Safety and regulatory requirements play a key role in shaping the system design. Handling metal powders places strict limitations on equipment, material flow, and possible automation solutions. This means that the system cannot be designed freely but must be adapted to these conditions, which aligns with contingency theory. For example, requirements such as full traceability, strict batch separation, and controlled material flows limit the available design choices. As a result, the layout, storage, and handling processes must be carefully structured to meet these constraints. In addition, the project is based on a brownfield context, meaning that the system must be designed within an existing facility with pre-defined constraints rather than a completely new (“greenfield”) environment. This further restricts design freedom and reinforces the need for solutions that adapt to existing conditions.

Finally, while there is an expressed ambition to increase automation or prepare the system for future automation, the empirical findings show that current constraints limit the immediate implementation of advanced solutions. This further reinforces the contingency perspective: rather than optimizing for maximum automation, the system is designed to achieve the best possible fit between current constraints and future adaptability.

Overall, the analysis demonstrates that the proposed logistics configuration is not an optimal solution in isolation, but rather a context-dependent design that balances efficiency, safety, flexibility, and feasibility within the given environmental conditions.

6. Logistics Configuration Analysis (concept development)

This section presents the second stage of the EPL-framework, focusing on the development of logistics configurations, see Figure 6-1. While the environmental analysis defined the system constraints, this stage translates those requirements into feasible design alternatives. The purpose is to structure and combine key design dimensions found in the logistics configuration workshop into preliminary concepts that can be evaluated in the next step.

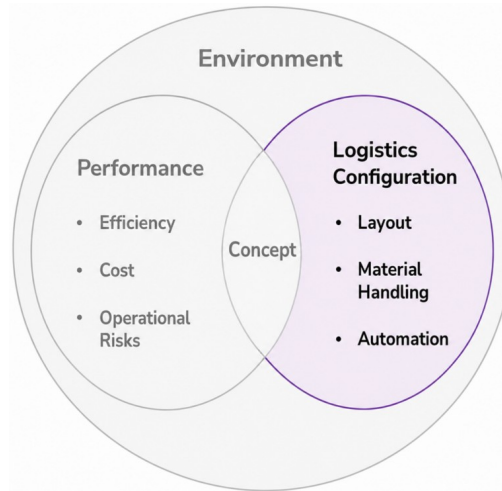


Figure 6-1. EPL Framework, Logistics Configuration highlighted.

6.1 Design Dimensions

The development of logistics configurations is based on a set of key design dimensions that represent the primary variables influencing the system design. The use of multiple dimensions is motivated by the need to adapt design decisions to a combination of conditions to achieve high system performance as highlighted by Drazin and Van de Ven (1985). These dimensions were identified from empirical findings gathered through interviews and the environment workshop.

The empirical data revealed three recurring decision areas that significantly impact the configuration of the system. First, volume was identified as a critical factor, as container sizes influence the number of material handling operations required. This establishes a direct link between volume decisions and the overall handling effort within the system. This is supported by Al-Zubaidi et al. (2021), who state that material handling can account for up to 50% of total operating costs, highlighting its significance in system design.

Second, layout structure emerged as a central dimension due to space constraints, fixed machine positions and the need for controlled and separated material flows. Al-Zubaidi et al. (2021) emphasize that layout design directly affects resource utilization and contributes to improved worker safety. This is further supported by Ramasu et al. (2025) who note that an effective layout can reduce material handling costs, work-in-process (WIP) and production time.

Third, automation was identified as an important dimension through discussions on reducing manual handling, improving safety and addressing workforce limitations. Bernardo et al. (2022) support this by highlighting several advantages of automation including increased scalability, reduced error rates and improved organizational control. In addition, Granlund and Wiktorsson (2014) emphasize that automation can lower costs and improve working conditions.

These dimensions were therefore selected as the primary variables for developing and comparing different logistics configurations. To limit the number of concept alternatives, the dimensions are initially treated individually and later combined into a final, refined concept.

6.2 Development of Preliminary Concepts

Two preliminary concepts were developed. This was primarily based on Nugraha and Soewarno (2024), who argue that there is no “one-size-fits-all” solution and that multiple approaches can be used when structuring new concepts and they further emphasize that organizations cannot simply adopt standardized solutions but must instead adapt them to their specific operational environment. This perspective is supported by Muther and Hales (2015), who highlight that layout design should not result in a single solution but instead in several alternative configurations. Developing multiple layout options increases the likelihood of identifying a more effective and well-functioning design.

Both proposed layouts can handle different production volume levels, although their performance and suitability may vary depending on the specific operational conditions and system demands. The first step in the SLP framework is to describe and list the functional areas that were done and shown in Table 6-1.

Table 6-1. Functional Areas.

Order of appearance	Name	Description
1	Powder In	Incoming powder deliveries
2	Goods Receiving	Receiving and initial handling of incoming goods
3	Buffer Zone	Temporary powder storage acting as a buffer to ensure supply in case of machine demand or disruptions
4	Storage Virgin	Storage of new powder with dedicated machine
5	Filling Powder Station	Tanks are filled with powder
6	Transport of Powder	Internal transportation of powder
7	Machine	Production process
8	DPS	Separation of powder from finished product
9	Powder Control	Quality inspection of used powder
10	Storage “Bad Powder”	Storage of powder not suitable for reuse
11	Powder Out	Outgoing goods handling

Next, the relationships between the activities were analyzed, focusing on which processes should be in proximity and what supporting functions are required. According to Palange and Dhattrak (2021), one of the core principles of lean production is the reduction of waste, including unnecessary transportation. By positioning closely connected activities near each other, transportation distances and unnecessary movement can therefore be minimized.

To support this analysis, a relationship chart was developed in accordance with the methodology proposed by Muther and Hales (2015). The resulting relationship chart is presented in Table 6-2.

Table 6-2. Relationship Chart

	Powder In	Goods Receiving	Buffer Zone	Storage Virgin	Filling Powder Station	Transport of Powder	Machine	DPS	Powder Control	Storage "Bad Powder"	Powder Out
Powder In		A	E	E	O	O	U	U	U	X	X
Goods Receiving	A		A	E	O	I	U	U	U	X	X
Buffer Zone	E	A		U	I	I	U	U	U	X	X
Storage Virgin	E	E	U		I	I	U	U	U	X	X
Filling Powder Station	O	O	I	I		I	O	U	U	X	X
Transport of Powder	O	I	I	I	I		I	I	I	I	I
Machine	U	U	U	U	O	I		U	I	O	U
DPS	U	U	U	U	U	I	U		E	U	U
Powder Control	U	U	U	U	U	I	I	E		O	U
Storage "Bad Powder"	X	X	X	X	X	I	O	U	O		A
Powder Out	X	X	X	X	X	I	U	U	U	A	

While space considerations are an integral part of the Systematic Layout Planning (SLP) framework, they were not explicitly addressed in detail in this study. Instead, the analysis primarily focused on activity relationships and practical constraints when developing alternative layout configurations, in accordance with Muther and Hales (2015). The fourth step in the SLP framework was to combine the relationships and constraints (in our case the environmental constraints identified). Automation considerations were also included during the layout development process. For both layout alternatives, a single-loop AGV/AMR layout structure, as described by Melo and Corneal (2020), was considered the most suitable option due to its relative simplicity and ease of implementation. More complex configurations such as conventional layouts would require wider transport lanes and larger modifications to the existing facility. Since the production environment and infrastructure are largely predetermined, the layout design needed to adapt to these existing constraints which is consistent with the observations presented by Melo and Corneal (2020). This resulted in two different layouts described in the next chapters.

However, the layout is a conceptual representation showing how functions are placed in relation to each other rather than exact positions. Only the selected layout will be developed in detail in later stages.

6.2.1 Layout 1 Constraint-driven

The development of Layout 1 was guided by the relationship analysis conducted within the SLP framework while simultaneously being constrained by existing spatial conditions. Based on the relationship chart, activities were assigned closeness ratings indicating the desired proximity between processes. High-priority relationships such as A (absolutely necessary) and E (especially important) were prioritized in the spatial arrangement to ensure that interdependent processes were located close to each other. For instance, the strong relationships between goods receiving, buffer storage and virgin powder storage motivated their close grouping, supporting a smooth transition from inbound handling to storage and preparation. Similarly, processes related to used powder handling, such as DPS, powder control and storage of used powder were deliberately located within the same area.

Conversely, activities assigned an X (undesirable) rating were deliberately separated in the layout. This is particularly evident in the placement of waste-related processes, such as storage of "bad powder" and powder out which are located away from core production and storage areas to minimize the risk of contamination and interference with primary material flows. Intermediate relationships (I and O) were

considered where feasible but were more strongly influenced by spatial and structural constraints. In this way, the relationship chart not only defined which processes should be close or separated but also directly influenced the zoning and overall structure of the layout.

At the same time, the design of Layout 1 is primarily constraint-driven and closely aligned with the initial layout presented in Figure 6-2. Existing spatial conditions, fixed machine positions and already occupied areas were treated as boundary conditions throughout the design process, significantly limiting the degrees of freedom. As a result, the layout reflects a series of necessary trade-offs between theoretical flow optimization and practical feasibility within the existing facility.

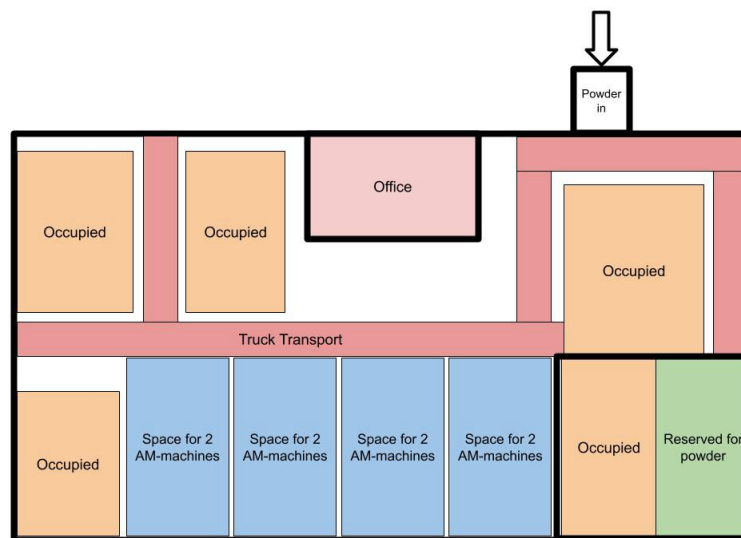


Figure 6-2. Layout proposal from the studied company.

These constraints prevented the development of a fully linear and optimized flow, requiring the layout to be adapted around existing structural conditions. This explains why certain material flow crossings remain unavoidable. To structure the internal separation of the system, principles from Holah (2011) were applied through a layered protection approach. External logistics areas represent the outermost level, followed by the factory environment and then progressively more controlled zones for powder handling. The most critical operations are in the innermost areas, ensuring increased control as materials move deeper into the system. This “box within a box” structure supports contamination prevention and controlled material handling.

In relation to flow logic, the design aims to support a forward-moving material flow in line with Drira et al. (2007), where backtracking and unnecessary transport loops are minimized. However, due to spatial limitations, a fully sequential system could not be achieved. This results in certain inefficiencies in material routing, although the overall direction of flow remains from inbound logistics towards production and finally waste or reuse handling.

From a capacity and bottleneck perspective, the positioning of high-activity processes such as DPS, powder filling and waste handling is a consequence of spatial constraints rather than ideal optimization. According to Tang et al. (2024), bottlenecks occur when demand approaches or exceeds resource capacity leading to congestion and reduced throughput. In Layout 1, the proximity of these interdependent processes increases the risk of local capacity pressure and shifting bottlenecks, particularly under higher production loads.

The relocation of the goods receiving area closer to production illustrates how empirical findings influenced the design. This adjustment reduces unnecessary transportation distances, lowers manual handling and improves traceability. At the same time, the layout reflects compromises between ideal

flow principles and spatial restrictions where certain process areas remain closer together than what would be optimal under unconstrained conditions.

Structurally, Layout 1 can be characterized as a process layout, where functional areas are organized according to their specific tasks and material is routed between different “departments” depending on process requirements (Ramasu et al., 2025).

The 5S principles were applied within the constraints of the existing system. As described by Ramasu et al. (2025), these consist of Sort, Set in Order (Systemize), Shine, Standardize, and Sustain. Sort focused on removing or relocating non-essential elements, while Set in Order structured resources in a sequential flow limited by fixed machine positions. Shine was addressed by minimizing inaccessible areas to support cleanliness and control, particularly important in powder handling environments. Standardization enabled scalability by allowing additional machines to be integrated into existing structures, although process clustering around DPS, filling and waste handling limits full scalability. Finally, Sustain was only partially achieved as the layout is still dependent on predefined structural constraints which reduces its long-term flexibility and may require reassessment if process conditions change significantly.

In summary, Layout 1 represents a compromise-driven solution where safety, traceability, and existing spatial conditions take precedence over pure flow efficiency. The resulting layout is therefore a pragmatic balance between theoretical design principles and real-world operational limitations. Layout 1 is displayed in Figure 6-3.

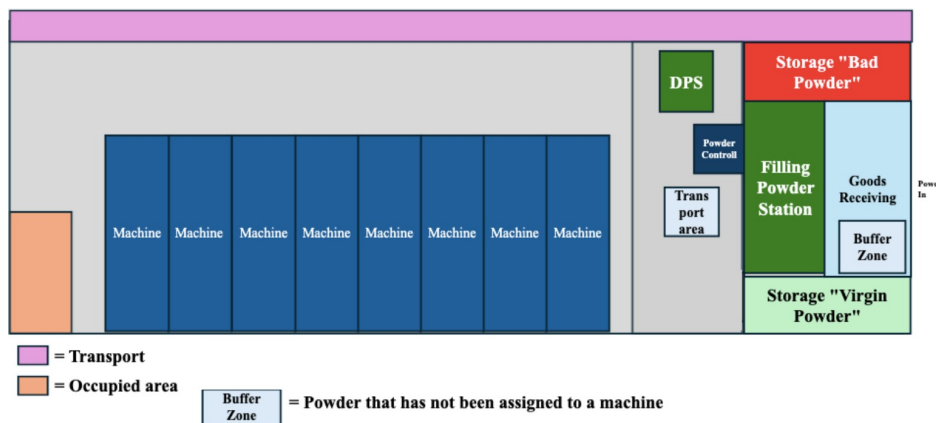


Figure 6-3. Layout 1.

Layout 1 can be considered partially compatible with automated material handling solutions such as Autonomous Mobile Robots (AMRs), as described by Melo and Correa (2020). A single-loop transport system could potentially be implemented, although its suitability depends on operational performance requirements and system-specific constraints.

6.2.2 Layout 2 Optimized Through Powder Perspective

The development of Layout 2 was guided by the relationship analysis conducted within the SLP framework, while allowing greater flexibility in the spatial arrangement compared to Layout 1. Based on the relationship chart, activities were assigned closeness ratings indicating the desired proximity between processes.

Intermediate relationships (I and O) were considered and implemented to a greater extent than in Layout 1, as the reduced spatial constraints allowed for a closer alignment between desired and actual proximity. This is reflected in the layout through smoother transitions between process steps, as powder transportation could be arranged more efficiently between machines. For example, transport areas are positioned in direct connection to both production and supporting functions, enabling efficient material

flow without unnecessary detours. As a result, the relationship chart had a stronger influence on the final layout structure, facilitating a more consistent translation of SLP principles into the spatial design.

Layout 2 is structured according to the batch separation principles described by Holah (2011), where material enters from one side of the facility and exits from the other. This results in a clear directional flow from inbound logistics, through storage and production, to reuse or waste handling. The spatial arrangement ensures that each process step naturally feeds into the next, reducing unnecessary movement and supporting a continuous material flow. Holah (2011) further emphasizes that effective batch separation can prevent cross-contamination, which is particularly important in powder handling processes. The zoning principles described by Holah (2011) were also implemented to maintain controlled separation between different stages of the process. Compared to Layout 1, these zones are more evenly distributed across the facility, allowing clear functional separation while avoiding excessive clustering of high-intensity operations. This contributes to a more balanced utilization of space and improved operational control.

From a flow perspective, Layout 2 achieves a more linear and balanced material movement compared to Layout 1. In line with Drira et al. (2007), backtracking and unnecessary transport loops are minimized, resulting in shorter transport distances and improved flow efficiency. The separation of high-activity processes across different areas further reduces congestion and enables a more even distribution of material handling activities throughout the system. The layout is also aligned with the product-oriented layout approach described by Ramasu et al. (2025), as it is structured around the sequential production steps, enabling a smooth powder flow through each stage. In addition, Layout 2 reflects the robust layout concept described by Ramasu et al. (2025), which is designed for long-term adaptability, as new machines can be integrated into the production line with minimal disruption.

From a capacity and bottleneck perspective, the distributed positioning of key processes such as DPS, powder filling, and waste handling reduces the risk of local capacity constraints. According to Tang et al. (2024), bottlenecks occur when demand equals or exceeds resource capacity. By avoiding clustering of interdependent processes, Layout 2 reduces the likelihood of local overload and shifting bottlenecks, particularly under higher production volumes.

The 5S principles are more systematically embedded in the design. As described by Ramasu et al. (2025), these consist of Sort, Set in Order (Systemize), Shine, Standardize, and Sustain. Sort was applied to remove unnecessary elements and organize processes into functional groups based on value-adding activities. Set in Order ensured a continuous and logical process sequence aligned with optimized flow rather than spatial constraints. Shine was improved through better accessibility and fewer congested areas, enabling easier cleaning and monitoring. Standardization created a modular structure that allows easy integration of additional machines without disrupting flow logic. Sustain is strengthened through a stable and coherent layout that reduces the need for reinterpretation and supports long-term operational consistency.

Finally, Layout 2 is compatible with automated material handling systems such as Autonomous Mobile Robots (AMRs), as described by Melo and Correa (2020). The structured and linear flow enables the potential implementation of a single-loop transport system, depending on operational requirements. This flexibility is further supported by the advantages discussed by Bernardo et al. (2022), which highlight the benefits of adaptable layout systems when implementing automation.

In summary, Layout 2 represents a flow-oriented and optimized layout in which the relationship analysis from the SLP framework is more fully realized due to fewer spatial constraints. The design prioritizes efficient material flow, reduced congestion and improved scalability, resulting in a more balanced and adaptable system compared to Layout 1. Layout 2 is presented in Figure 6-4.

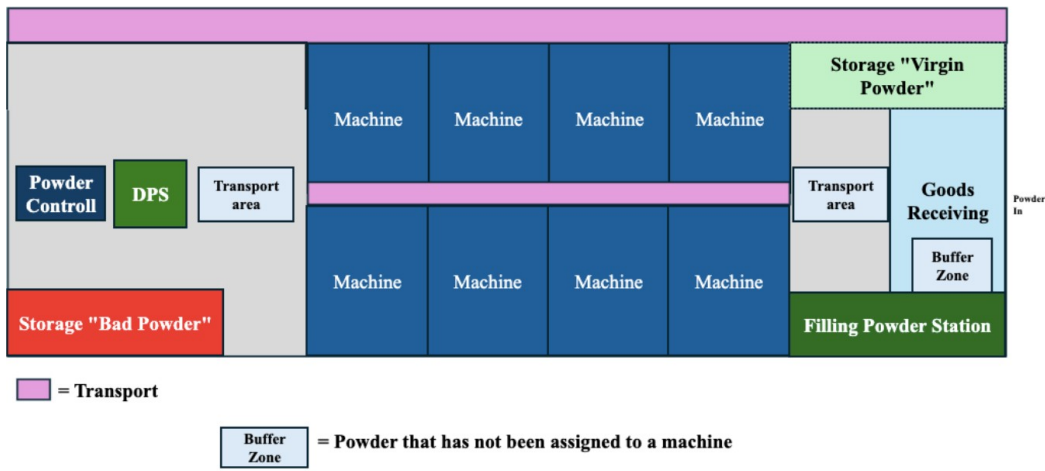


Figure 6-4. Layout 2.

6.3 Excluded Design Alternatives

During the concept development, several potential design alternatives were considered but not included in the final analysis. These include pipe-based transport systems, supplier-filled SLM tanks and high levels of automation.

Pipe-based systems were excluded due to their lack of flexibility and the restrictions they impose on layout design, particularly in a dynamic and constrained environment. Supplier-filled tanks were not considered feasible due to concerns related to contamination risk, cost and handling complexity outside the controlled production environment. Additionally, in-house tanks other than SLM tanks were excluded based on the results from the environmental workshop which indicated potential risks of contamination and increased handling complexity. Finally, higher levels of automation were limited by high costs, safety requirements and the need to maintain compatibility with existing equipment.

Overall, these alternatives were excluded as they did not align with the identified environmental and operational constraints of the system.

6.4 Evaluation Workshop

This section presents the findings from the concept evaluation workshop, where participants assessed the proposed logistics configurations and discussed key aspects including powder flow (layout solutions), unit volumes and automation. The outcomes helped define the final boundaries and guide the selection of the final concept.

The results from the evaluation workshop provided key insights related to material handling, risk, and layout design decisions. An important part of the workshop was to validate the proposed layouts, confirming that they are feasible within the actual production environment and can function in practice. This ensured that the layouts are not only theoretically sound but also operationally realistic. Both proposed layouts were approved as feasible, and it was confirmed that the original layout could be restructured so that for example the “powder in” function could be relocated within the workshop to improve overall flow. As initially identified in the environmental workshop and further reinforced in the Evaluation workshop, traceability is critical, requiring all powder containers to be equipped with identification such as barcodes or RFID tags.

Another important outcome was the requirement to destroy used tanks due to contamination risks. This implies that larger, self-designed tanks would not be cost-efficient as new tanks would need to be produced for each incoming batch. Furthermore, several handling risks were discussed. A key risk was identified in manual forklift operations when positioning tanks onto machines. Automation solutions, such as overhead cranes were considered to reduce these risks and ensure consistent positioning.

However, these solutions were not prioritized, highlighting a trade-off between improved safety and increased implementation complexity.

It was also concluded that the entire workshop area must be temperature controlled ($20 \pm 2^\circ\text{C}$). This enables decentralized storage, as powder can be stored throughout the facility, increasing flexibility in the final logistics configuration. One suggestion raised during the workshop was to locate storage near the machines by developing a cell-based structure for powder handling. In this concept, each production cell would include local storage and serve multiple machines within the same cell. Material handling would be restricted to a shared area within each cell, aiming to improve control and organization of powder flow. Figure 6-5 shows an example of how this could be implemented.

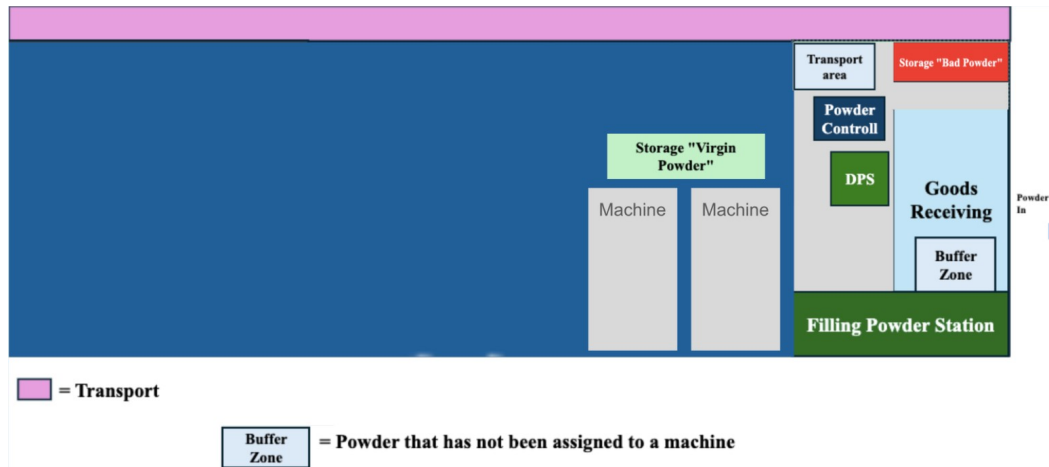


Figure 6-5. Layout 3

All participants agreed that the use of 100 kg tanks is the most suitable solution, primarily due to cost and efficiency considerations. Although automation was discussed, it was not considered relevant in the initial implementation phase due to its complexity and cost.

In conclusion, the workshop provided a clear and practical foundation for the final concept by validating the feasibility of the proposed layouts, identifying key constraints and aligning technical possibilities with operational realities, thereby ensuring that the selected solution is both implementable and robust in practice.

7. Performance

Finally, the fifth step of the SLP framework involves evaluating the proposed layouts based on different criteria, see Figure 7-1.

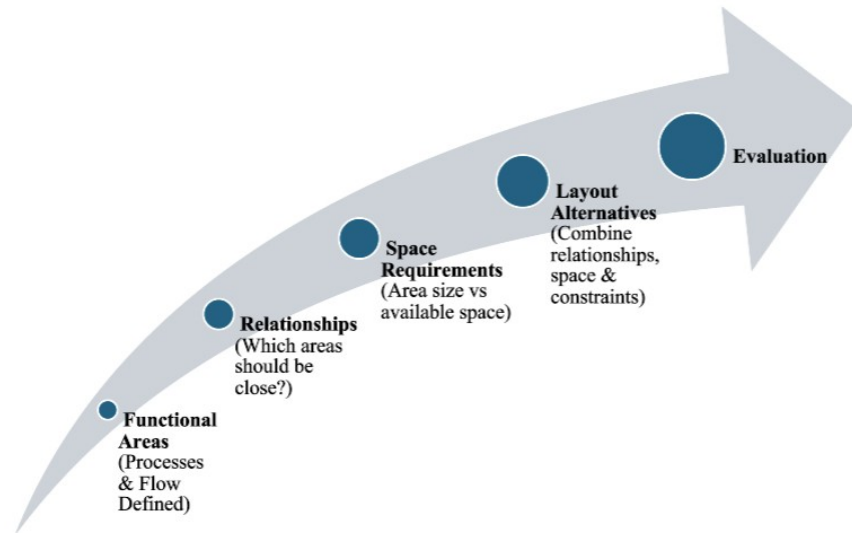


Figure 7-1. SLP Steps based on Muther and Hales (2015).

This corresponds to the third step of the EPL framework, where the performance of the developed logistics configurations is assessed using defined performance metrics as seen in Figure 7-2.

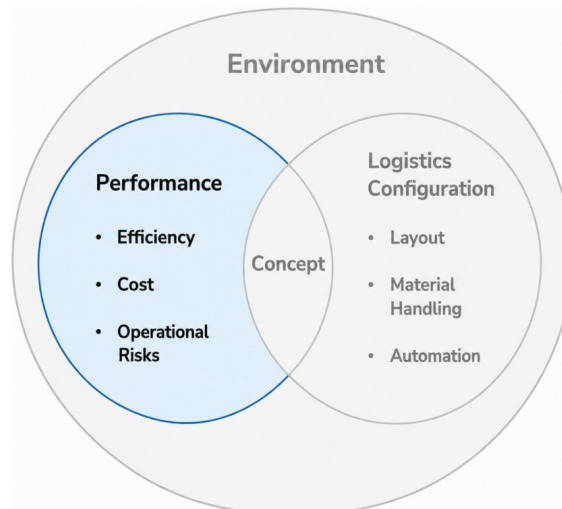


Figure 7-2. EPL Framework, performance highlighted.

The evaluation therefore focuses on how the proposed powder-logistics concepts perform in relation to efficiency, investment cost, tied-up capital in powder and safety. An overview of the analyzed performance areas is presented in Table 7-1.

Table 7-1. Performance area and how they are measured.

Area	What is measured?	How it is measured
7.1 Layout	Layout performance (flow, risk, feasibility)	Comparison of risk and feasibility assessment
7.2 Investment cost	The cost of equipment needed.	Estimated calculations
7.3 Efficiency	Number of handling points in the complete flow.	MFM and HATS table
7.4 Tied-up capital	The tied-up capital in powder per machine.	Estimated calculations
7.5 Operational Risks	Risks of each choice, what is the impact and how can it be reduced?	Risk matrix

7.1 Layout evaluation and selection

This section evaluates the three developed layout alternatives to assess their suitability for efficient powder logistics. The evaluation considers material flow performance, operational risk, scalability and implementation feasibility within the existing production environment.

7.1.1 Layout Comparison

Table 7-2 below presents a comparative analysis of the three layout concepts in terms of their main advantages and disadvantages. The evaluation is based on the performed risk analysis where both qualitative system characteristics and quantified risk levels have been considered. Each layout is assessed with respect to operational performance, material flow structure and key risk factors such as congestion, contamination and traceability, allowing for a direct comparison of their overall suitability.

Table 7-2. Layout Evaluation, Positive vs. Negative

Layout	Positive	Negative
1	Centralized powder handling simplifies coordination, supervision, and communication. Short transport distances between storage and filling improve efficiency and make the layout easy to implement within existing facility constraints.	High risk of congestion, bottlenecks, and cross-contamination due to shared handling of multiple powder types. Increased probability of mix-ups and traceability errors results in the highest total risk level (164) (see appendix)
2	Separation of virgin and used powder improves contamination control and traceability through clear material flows. This reduces congestion and supports structured logistics, resulting in the lowest total risk level (81) (see appendix)	Requires more space and increases system complexity due to dedicated handling areas. Risk reduction is mainly driven by lower probability

		rather than reduced consequence in critical risk areas.
3	The decentralized layout creates a direct connection between each machine and its assigned powder batch, which improves traceability and reduces the need for additional identification systems such as pick-by-light. Storage levels can be visually monitored at each machine, simplifying operational control and replenishment planning. The concept also supports high operational flexibility.	Longer transport distances and duplicated storage reduce space efficiency. Increased operational complexity and remaining issues with congestion and bottlenecks result in a moderate total risk level (89) (see appendix)

Overall, the comparison highlights a clear trade-off between risk level, spatial efficiency and operational simplicity. Layout 1 offers a compact and integrated solution and Layout 2 achieves the lowest risk through strong separation of flows while Layout 3 provides higher flexibility at the cost of increased operational complexity.

7.1.2 Layout Selection

To support the final decision, a pairwise comparison of the three alternatives was conducted. Each layout was evaluated against the others in terms of operational feasibility, material flow performance and system suitability within the existing production context. The results are summarized in Table 7-3 and form the basis for the final selection.

Table 7-3. Layout Comparison.

Comparison	Preferred layout
Layout 1 vs Layout 2	Layout 1
Layout 1 vs Layout 3	Layout 1
Layout 2 vs Layout 3	Layout 3

The choice of Layout 1 over Layout 2 is primarily based on contingency theory as described by Drazin and Van de Ven (1985) which argues that there is no universal optimal solution and that system design must be adapted to its specific operational context. Layout 2 is largely developed from a “greenfield” assumption where the layout is designed from a blank slate. However, the production environment at the studied company is a brownfield setting with fixed machine positions and limited spatial flexibility. In this context, extensive modifications to machine placement or the addition of new aisles would be both costly and difficult to implement making Layout 1 a more feasible and economically viable solution. This is further supported by Muther and Hales (2015) in their description of Systematic Layout Planning (SLP) which emphasizes minimizing material flow distances and prioritizing proximity between related activities. Layout 1 aligns with these principles by grouping key functions such as material reception, buffer storage and powder filling within proximity, thereby improving flow efficiency and reducing unnecessary material handling.

When comparing Layout 3 to Layout 2, the cell-based structure of Layout 3 provides stronger support for traceability and operational control. Empirical findings from the evaluation workshop highlight that batch-level traceability is a critical requirement. Layout 3 addresses this by creating a clear link between each batch and its corresponding machine (by having storage close to the machine), reducing the risk of incorrect powder usage. This approach is also consistent with cellular layout principles described by

Ramasamy et al. (2025) where production is organized into “mini factories” to reduce uncontrolled material movement and improve local control.

Despite these advantages, Layout 1 is still considered more suitable than Layout 3 for the specific operational context. Layout 3 requires longer transport distances for powder replenishment which increases operational workload and adds complexity to the material flow. In contrast, Layout 1 centralizes all powder handling activities within a single dedicated area, resulting in shorter internal transport distances and a more controlled and predictable material flow. In addition, this centralized structure improves control over contamination risks and ensures clearer separation between material types such as virgin and “bad powder”. From a safety perspective, it also facilitates the implementation of strict fire protection and “hazardous” zones compared to distributing these high-risk operations across the entire workshop floor.

Overall, while Layout 2 and Layout 3 offer advantages in specific areas such as risk reduction and traceability, Layout 1 provides the most feasible and context-adapted solution in terms of implementation, operational control and integration with existing facility constraints. Therefore, Layout 1 is selected for further development.

7.2 Investment Costs

This section presents the investment costs required to implement the proposed material handling solution. Since Layout 1 was selected for further development, the investment analysis focuses on the equipment, storage solutions, identification systems and transport support needed to make this layout operational. The purpose of the analysis is not to provide a final procurement calculation, but to identify the main investment areas and compare their relative cost impact. The cost analysis is therefore seen as a planning-level estimate, intended to support selection and future implementation decisions.

Layout 1 is based on a compact and centralized structure. This reduces the need for duplicated storage and handling equipment compared with more decentralized alternatives. However, it also places higher requirements on shared handling points, clear identification routines and reliable lifting equipment, since several powder flows are coordinated through the same logistics structure. The main investment needs are therefore connected to three areas, storage and identification systems, lifting and handling equipment, and internal transport equipment.

7.2.1 Investments to support Layout 1

The selected layout requires investments at each critical point in the flow. The investment needs are derived from the activities that must be supported in the future state. Table 7-4 summarizes the main investments required to support Layout 1.

Table 7-4. Investment per Area.

Layout Area	Required investment	Purpose	Cost Estimate
Goods receiving	Crane or lifting device, customized lifting attachment, receiving pallet or fixture	Safe handling of incoming 100 kg powder containers	High
Storage zones	Marked pallet positions, storage racks or floor zones, batch separation areas	Controlled storage of virgin and used powder batches	Low
Identification system	RFID/barcode tags, scanners/readers, digital registration routines	Ensure traceability between batch, container, tank and machine	Medium

Pick support	Pick-by-light or visual guidance system	Reduce risk of selecting wrong batch or material	Medium
Filling area	Crane with rotating lifting attachment	Enable safe and ergonomic filling from 100 kg containers	High
Machine area	Lifting support for SLM tanks or fixed crane solution	Position and handle SLM tanks safely at the machines	High
Internal transport	Manual pallet truck, forklift, tugger or AMR/AGV solution	Move powder containers and tanks between storage, filling and machines	Low–High depending on automation level
Layout implementation	Floor markings, safety zones, traffic lanes and signage	Create controlled and safe movement paths	Low

The investment analysis shows that the largest cost drivers are expected to be lifting equipment at machine and filling points, followed by identification systems and possible transport automation. Storage markings and layout implementation are expected to have lower direct investment cost, but are still important because they support traceability, safety and operational control.

7.2.2 Storage and Identification Systems

A central investment area for Layout 1 is the storage and identification system. Since Layout 1 is based on a centralized structure, several powder flows are coordinated through shared storage and handling areas. This makes it necessary to clearly separate powder by batch identity and powder condition. Without a structured storage and identification system, the centralized layout would increase the risk of incorrect material selection and loss of traceability.

From a theoretical perspective, this is closely related to workplace organization and error prevention. Ramasu et al. (2025) describe 5S as a Lean method for creating an organized, efficient and safe workplace through sorting, systemizing, cleaning, standardizing and sustaining routines. In the context of Layout 1, this means that storage positions should be clearly defined, visually marked and standardized so that operators can quickly identify where each powder unit belongs. This supports both efficiency and safety by reducing unnecessary searching, movement and uncertainty in daily operations.

The need for clear storage control is also supported by the physical and spatial constraints discussed in the theoretical framework. Al-Zubaidi et al. (2021) emphasize that limited storage areas can become bottlenecks if capacity is not controlled, especially in environments where production volume increases. For Layout 1, this means that storage areas must be dimensioned and organized so that powder containers, SLM tanks and used powder do not block the flow or create unclear temporary storage locations. The investment should therefore include marked floor positions, batch-specific storage locations and dedicated zones for different powder states.

Identification systems are also required to support traceability throughout the powder-logistics flow. In this study, traceability is treated as a mandatory requirement rather than a performance option. Each powder batch must be connected to the correct container, SLM tank, machine and reuse history. Therefore, investments in barcode scanning, RFID or similar digital identification systems are needed to reduce the risk of manual errors and ensure that powder movements can be registered consistently. This is particularly important in Layout 1 because several batches may pass through the same centralized handling points.

The theoretical relevance of such systems is supported by the literature on RFID and error-proofing. RFID can be used to identify and track objects automatically, which makes it useful in logistics systems where material identity must be maintained across several process steps. In this context, RFID can support more reliable material flow control by ensuring that each batch is correctly registered at each step of the process. Compared to traditional barcode systems, the ability to read multiple tags simultaneously also reduces handling time and the need for operator interaction. Schmidt et al. (2013) further highlight that RFID systems typically consist of tags attached to objects and readers integrated into equipment such as handheld devices or fixed gates which are connected to digital systems for real-time data handling. This integration enables improved traceability throughout production and logistics operations.

A possible additional investment is a pick-by-light or visual guidance system in the storage area. This would help operators select the correct powder unit and reduce dependence on memory or manual checking. Although this would increase the initial investment cost, it could reduce operational risk by supporting correct material selection and improving traceability. This is especially relevant if the number of powder batches, machines or operators increases in the future.

Overall, the investment cost for storage and identification systems is assessed as low to medium for physical storage solutions and medium for digital identification systems. Marked storage positions and visual separation can be implemented at relatively low cost, while RFID or pick-by-light integration require higher investments. However, these systems are important enablers for Layout 1 because they allow the centralized flow to remain controlled, traceable and scalable as production volume increases.

Table 7-5. Summary of supporting systems.

System	Investment items	Function
RFID	Tags, scanners, readers, software	Links tank/batch to machine
Pick by light	Light modules, controller, installation	Guides operators to correct storage location
Visual marking	Labels, floor markings, signs	Supports manual handling and safety
Batch tracking	Database or system integration	Ensures traceability

7.2.3 Lifting and Handling Equipment

Lifting and handling equipment represent one of the most important investment areas for Layout 1. The future powder flow is based on larger powder units than the current setup, which means that manual lifting and handling should be avoided. 100 kg powder containers require dedicated lifting support at goods receiving, filling and potentially near the machine area.

At goods receiving, a fixed or semi-fixed crane solution is required to unload and position incoming powder containers safely. The main purpose of this investment is to reduce manual handling, improve ergonomics and enable standardized handling from the first step of the flow. Within the framework of a material handling system (MHS) explained by Amjath et al. (2023) this corresponds to the design-related features, since the choice of lifting equipment directly influences the system's structure and configuration. A pillar jib crane with sufficient capacity can be installed to lift the container from the incoming pallet or transport unit. In addition, a custom lifting attachment is required to connect the container to the crane hook. Since the exact design of this attachment has not yet been defined, it should be treated as a custom-manufactured investment item.

At the filling area, the lifting requirement is more complex. In addition to lifting the container, the equipment should also support controlled rotation or tilting so that powder can be transferred safely into

the next tank. This means that the filling point requires either a crane with a rotating lifting attachment or another purpose-built fixture. This is likely to be one of the more expensive investment items, but it is also critical for making larger powder units operationally feasible.

At the machine area, lifting support is required for handling SLM tanks. Since SLM tanks are heavy and must be positioned accurately, a mobile crane or equivalent lifting device should be available at each relevant machine position. Mechanical stops or fixed positioning aids can be added to ensure that the tank is placed in the same position each time. This reduces variation in the handling process and supports safer, more repeatable operations.

The cost impact of lifting and handling equipment is therefore assessed as medium to high. It is a necessary investment for Layout 1, since the layout cannot support high-volume powder handling safely if operators remain dependent on manual or improvised lifting solutions.

7.2.4 Internal Transport Alternatives and Future Automation

Internal transport is one of the investment areas where the difference between a low-investment and a future-oriented implementation of Layout 1 becomes most visible. Since Layout 1 is based on a compact and centralized structure, transport distances are expected to be relatively short and controlled. This means that manual transport can support the initial production phase with a lower investment cost. However, if the layout is evaluated from a long-term high-volume perspective, AMR/AGV-supported transport becomes more attractive.

In this study, manual transport refers to operator-controlled transport solutions, including pallet trucks, electric pallet trucks, forklifts, tugger solutions or dedicated powder transport carts. These solutions have a lower initial investment cost and can be implemented with limited changes to the facility. The main advantage is therefore flexibility during the early ramp-up phase. However, the transport task remains dependent on operator availability, manual prioritization and repeated human interaction with powder containers and SLM tanks. As the number of machines increases, this may create waiting time, interruptions and higher workload for operators.

The alternative is AMR/AGV-supported transport. This requires a higher initial investment, including vehicles, charging infrastructure, traffic routes, safety systems, pick-up and drop-off positions and integration with digital routines. In the early phase, when only a limited number of machines are installed, the utilization rate of the AMR/AGV system would likely be low. From a narrow short-term cost perspective, this makes automation difficult to justify. However, low utilization during the ramp-up phase can also be viewed as an implementation advantage. It gives the organization time to test, adjust and stabilize the automated transport system before the shop reaches full production volume. This reduces the risk of introducing automation later when the flow is already under pressure from higher machine utilization and more frequent powder movements.

From a long-term perspective, early AMR/AGV implementation also has an important equipment effect. If AMR/AGV transport can place the SLM tank in a fixed and repeatable position at the machine, the need for dedicated cranes at each machine may be reduced or removed. This changes the investment comparison. Manual transport requires local lifting support, such as cranes or lifting devices at the machine area, to position the SLM tanks safely and accurately. An AMR/AGV solution, in contrast, can be designed with fixed docking points and repeatable positioning, which supports safer and more standardized tank handling. This also reduces variation in the process and lowers the dependency on operator skill during positioning.

The theoretical framework supports this trade-off. Automation can improve scalability, process control, repeatability and the working environment, while also reducing errors in internal logistics (Bernardo et al., 2022; Granlund & Wiktorsson, 2014). At the same time, AMR/AGV systems require suitable layout conditions, such as defined traffic routes, sufficient aisle width and controlled pick-up and drop-off points (Melo & Corneal, 2020). Layout 1 is therefore suitable for future automation because its centralized structure creates limited and repeatable transport routes.

Table 7-6. Comparison between manual or automated handling of powder tanks.

Evaluation factor	Manual	AGV/AMR	Preferred
Initial investment cost	Low-medium	High	Manual
Utilization rate	High, operators can be used flexibly	Low	Manual
Learning Potential	Limited, system depends on operator routines	High, low early utilization gives time to test and optimize the system	Automated
High-volume readiness	Lower, more machines increase operator workload	Higher, system is already standardized before volume increases	Automated
Need for cranes at machines	Medium, possible with truck but safer with crane	Lower, if AMR/AGV can dock and position tanks repeatably	Automated
Repeatability of tank positioning	Depends on operator and lifting method	High, if fixed docking points are used	Automated
Operator workload	Higher, especially when transport frequency increases	Lower, as repeated transport work is automated	Automated
Safety and ergonomics	Risk analysis 87, Improved with aids, but still operator-dependent	Risk analysis 64, Better potential due to less manual interaction and repeatable movement	Automated
Scalability	Additional machines increase manual transport demand	Designed to absorb higher future transport frequency	Automated
Implementation complexity	Low	High	Manual

The comparison shows that manual transport is preferable only when the focus is limited to initial investment cost and short-term implementation simplicity. AMR/AGV transport performs better in most long-term factors, especially scalability, repeatability, operator workload and high-volume readiness. The main disadvantage is that the system would have a low utilization rate in the beginning. However, in a ramp-up situation, low utilization creates an opportunity to develop the system under stable conditions, adjust routes, verify docking accuracy, train operators and connect the transport system to identification routines before production volume increases.

Therefore, AMR/AGV-supported transport can be considered the better strategic investment for Layout 1, provided that the studied company accepts a higher initial investment and lower short-term utilization. Manual transport remains the lower-cost alternative for the first implementation stage, but it risks becoming a temporary solution that later needs to be replaced or supplemented. If the objective is to prepare the layout for a future high-volume LPBF shop, AMR/AGV transport is the more suitable alternative because it supports repeatable tank positioning, reduces the need for machine-area cranes and creates a scalable transport structure before additional machines are installed.

7.2.5 Summary of Investment Cost impact

The investment analysis shows that Layout 1 can be implemented without duplicated equipment because the layout is compact and centralized. This makes the layout attractive from an investment perspective compared with more decentralized solutions. However, the shared structure also means that some equipment must be reliable and well controlled, especially lifting equipment, identification systems and storage control.

The most critical investments are lifting equipment, since these are required to handle larger powder units safely. The second most important investment area is digital identification, as this supports traceability and reduces the risk of batch mix-ups in the centralized flow. Storage markings, safety zones and transport routes represent smaller investments, but they are necessary to make the layout understandable and operationally stable.

Overall, Layout 1 is expected to require a moderate investment level. The main advantage is that the concept can be implemented stepwise. Basic storage zones, identification routines and manual or assisted transport can be introduced first, while more advanced systems such as pick-by-light and AMR/AGV transport can be added later if production volume increases. This makes Layout 1 suitable as a robust and scalable starting point for the high-volume LPBF shop.

7.3 New Material Flow Efficiency

Efficiency was evaluated by comparing the number of logistics activities required in the current 10 kg powder flow with the proposed 100 kg flow. The analysis was based on Material Flow Mapping and the HATS classification, where activities are grouped as Handling, Administration, Transportation and Storage. This approach is suitable because powder-logistics activities are mainly necessary support activities rather than direct value-adding production steps. By classifying the activities, the analysis makes it possible to identify where the proposed flow reduces operational workload. The new MFM for 100 kg flow can be seen in Figure 7-3.

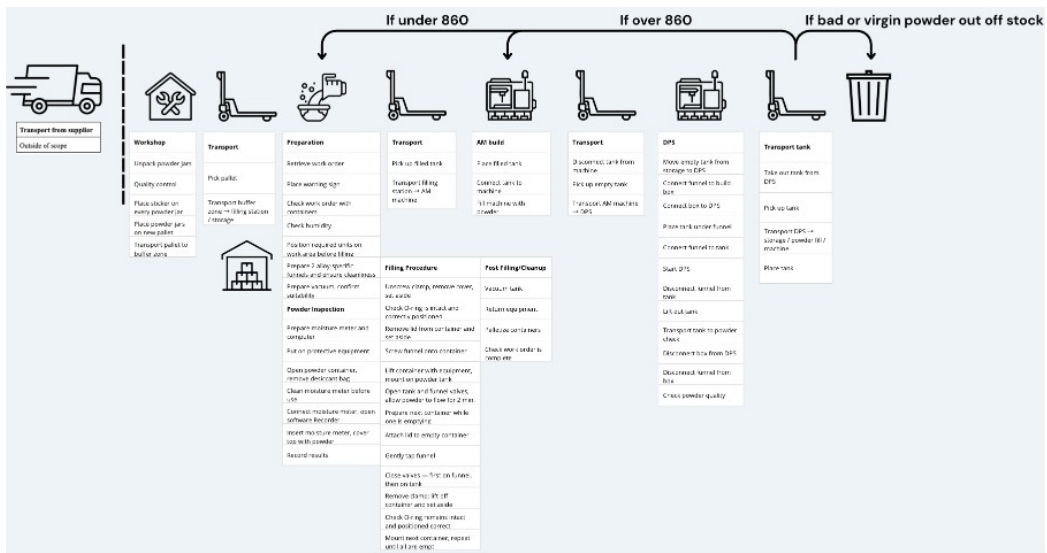


Figure 7-3. New Material Flow Mapping.

To enable a fair comparison between the current 10 kg flow and the proposed 100 kg flow, both alternatives were evaluated using the same batch size and production logic. The purpose of these assumptions is to translate the process maps into a frequency-adjusted HATS analysis, where each activity is multiplied by the number of times it occurs during one full powder batch. The comparison is based on a 2000 kg powder batch over an assumed period of approximately three months. Powder is assumed to arrive from the supplier on pallets containing 500 kg, and the same 500 kg capacity is

assumed for the new internal pallets. The production loop is based on an initial machine fill of 1100 kg, followed by three DPS-to-machine cycles where each cycle requires a refill of 300 kg. These assumptions create a consistent basis for comparing how many activities are required in each flow.

Table 7-7. HATS comparison between current and proposed powder flow.

	Old flow [number of points]	New flow [number of points]	Old flow [10kg jars included, 2000kg batch]	New flow [100kg jars included, 2000kg batch]
Handling	45	41	3 210	556
Administration	17	13	847	132
Transport	8	7	61	60
Storage	2	2	2	2
TOTAL	72	63	4 120	750

The HATS comparison shows two different types of efficiency improvement. First, when each activity is counted once, the number of identified process points is reduced from 72 to 63. This corresponds to a reduction of 9 process points, or approximately 12.5%. This indicates that the proposed flow is structurally less complex than the current flow. The reduction is mainly explained by removing separate goods receiving and truck-related handling steps and by creating a more direct flow into the workshop.

The largest operational saving becomes visible when the activities are weighted according to how many times they must be performed for one full batch. In the current 10 kg flow, the total number of activities amounts to 4120 per full batch. In the new 100 kg flow, the corresponding number is reduced to 750 activities. This equals a reduction of 3,370 activities, or over 80%. A lot of the activities are not very time consuming but since this is just for 1 machine, the saving becomes even larger when multiplied with the number of machines.

This result supports Finnsgård et al (2011) Material Flow Mapping logic, where material supply activities are made visible by categorizing them into Handling, Administration, Transportation and Storage. Since many material supply activities are necessary but do not directly increase product value, reducing repeated handling and administration represents an important efficiency improvement. The result also supports Palange and Dhattrak (2021) lean production perspective, where unnecessary handling, transportation and administrative work can be interpreted as waste. In this case, the 100 kg flow reduces waste mainly by reducing repeated jar-level activities rather than by changing the transport structure itself.

From an operational perspective, the reduction from 4,120 to 750 activities per full batch improves the scalability of the powder-logistics system. In a high-volume LPBF environment, the number of powder movements and machine-related activities will increase compared with the current demonstrator environment. If the current 10 kg flow were scaled up, the repeated handling and administration would risk creating an operator-dependent logistics system. This can be related to Tang et al. (2024) bottleneck theory, where human resources may become bottlenecks if the workload exceeds available capacity. By reducing the number of repeated activities, the proposed 100 kg flow reduces the risk that operator availability becomes a limiting factor in future production.

However, the analysis also shows that the 100 kg flow does not eliminate the need for controlled handling. Instead, it changes the nature of the work. The current flow is characterized by many repeated low-weight handling activities, while the proposed flow is based on fewer but heavier handling events.

This means that the efficiency gain depends on the availability of suitable lifting equipment, standardized procedures and safe positioning methods. The evaluation workshop supports the 100 kg solution as the most suitable alternative due to cost and efficiency considerations, while automation was considered too complex and costly at this stage because it would not remove the most critical manual powder-handling step.

Overall, the efficiency analysis shows that the proposed 100 kg flow provides a substantial reduction in operational workload. The total frequency-adjusted number of activities is reduced by approximately 81.8%, mainly through fewer handling and administrative activities. Transportation and storage are almost unchanged, which indicates that the main efficiency improvement comes from changing the powder unit size rather than changing the transport pattern. Therefore, the proposed flow provides a more scalable and less labor-intensive powder-logistics configuration for the future high-volume LPBF shop.

7.4 Tied-up Capital Powder

Powder handling strategy has a major impact on working capital requirements in metal additive manufacturing. Since metal powder is a high-value consumable material, the amount of powder stored in active production, standby inventory, and safety stock directly affects the total tied-up capital of the production system.

There are several factors that influence powder-related tied-up capital. Restrictive powder handling rules require larger operational powder buffers to maintain machine availability, while more flexible mixing strategies can reduce stranded inventory and improve powder utilization. However, increased flexibility normally also reduces traceability and makes quality assurance more complex.

To compare the different powder handling strategies, a common set of assumptions is used throughout the analysis. The scenarios are evaluated based on active production inventory and average powder inventory during the batch cycle. Safety stock is evaluated separately, since the required safety stock depends on the selected powder handling strategy.

Table 7-8. Powder handling assumptions used for tied-up capital calculations.

Parameter	Value
Powder price	750 SEK/kg
Machine powder capacity	1200 kg
Initial tank fill level	1100 kg
Minimum powder level to start build	860 kg
Powder consumption per build	95kg
Powder packaging size	100 kg
Build frequency	2 builds/week/machine

Each machine is assumed to have two SLM tanks. One tank is used in active production, while the second tank is used as a backup or transition tank. If the active tank is unavailable or falls below the minimum required powder level, the second tank can be prepared with the next approved powder batch or powder pool.

The analysis assumes that powder quality remains acceptable throughout the evaluated reuse cycle. Powder removal is therefore driven by operational and traceability constraints rather than metallurgical degradation. In the restricted scenarios, powder must be removed from operational inventory when it falls below the minimum operating level or when the maximum allowed utilization limit is reached. Removed powder is assumed to be handled as waste or sold back to the supplier, unless another approved reuse route is available. The following scenarios are evaluated:

- One batch per machine.
- Increased batch size
- Two batches combined
- Fully flexible powder pool

These scenarios represent increasing levels of powder handling flexibility. The first scenario provides the highest traceability but also creates the most stranded powder. The later scenarios improve powder utilization and reduce tied-up capital but introduce increasing traceability and quality assurance complexity.

7.4.1 One Batch per Machine

In this scenario, powder batches are handled as separated material flows. Powder from different batches may not be mixed, and the batch identity must be tracked. Virgin powder from the same batch may be added as a controlled top-up, while top-up events and reuse history must be recorded for traceability. This provides the highest level of traceability and simplifies quality assurance, since each machine operates with an isolated powder flow.

Each machine is assigned two SLM tanks. One tank is used in active production, while the second tank is kept as a backup. The backup tank is only used if the active tank is unavailable or when the active tank falls below the operational limit. In that case, the second tank can be filled with a new batch and become the next main production tank. Powder remaining below the operational limit must be emptied into another container for waste handling or sell-back, so that the tank can be released for use again as soon as possible.

Table 6-9. Simulation of powder consumption and powder inventory, 1 batch/machine.

Step	Powder level Tank [kg]	Storage level Batch [kg]	Total Powder [kg]
Start fill	1100	900	2000
After 3 builds	$1100-285=815$	900	1715
Top up 300 kg	1115	600	1715
After 3 builds	$1115-285=830$	600	1430
Top up 300 kg	830	300	1430
After 3 builds	$1130-285=845$	300	1145
Top up 300 kg	845	0	1145
After 3 builds	$1145-285=860$	0	860
After 1 build (13)	$860-95=765$	0	765

Since the powder level after 12 builds is exactly 860 kg, the tank can support one additional build if 860 kg is accepted as the minimum start level. After this 13th build, the remaining powder level is 765 kg and must be emptied into another container for waste handling or sell-back. This utilizes 61.75% of each batch which is under the limit of 67%.

Over the three-month cycle, the total powder inventory decreases from 2000 kg to 765 kg. The average total powder level during this period is therefore approximately 1383 kg per machine. This corresponds to an average tied-up capital of approximately 1.05 MSEK per machine. The scalability of tied-up capital is linear with the number of machines.

With the same strategy, a larger batch can be split across multiple machines. For example, a 4000 kg batch can supply two machines using the same logic. In this case, the total average inventory doubles, but the average inventory per machine remains the same, provided that the number of machines is even and each batch can be divided evenly between two machines. A downside with this is that the safety stock is increasing.

7.4.2 Increased Batch size

Another option to consider is increasing the effective batch size per machine from 2000 kg to 2300 kg. This batch size better matches the operational constraints of the tank system while remaining below the maximum allowed powder utilization limit of 67%. The simulation of this case can be seen in Table 7-10.

Table 7-10. Simulation of powder consumption and powder inventory, increased batch size.

Step	Powder level Tank [kg]	Storage level Batch [kg]	Total Powder [kg]
Start fill	1100	1200	2300
After 3 builds	1100-285=815	1200	2015
Top up 300 kg	1115	900	2015
After 3 builds	1115-285=830	900	1730
Top up 300 kg	830	600	1730
After 3 builds	1130-285=845	600	1445
Top up 300 kg	845	300	1445
After 3 builds	1145-285=860	300	1160
Top up 300 kg	1160	0	1160
After 3 builds	1160-285=875	0	875
After 1 build (16)	875-95=780	0	780

The tank is initially filled with 1100 kg, then additional virgin powder can be added in increments of 100 kg when required. With the assumed consumption of 95 kg powder per build, a 2300 kg batch can support 16 builds before the remaining powder must be removed from operational inventory. The total powder consumed during these builds is $16 \times 95 = 1520$ kg. This corresponds to a batch utilization of 66.1% and the average powder inventory during the batch cycle is therefore $(2300+780)/2 = 1540$ kg with an average tied-up capital of 1.16 MSEK per machine

Compared with the 2000 kg batch case, the 2300 kg batch increases the number of builds per batch and improves powder utilization while still respecting the 67% maximum reuse limit. However, the larger batch also increases average tied-up capital per machine. The benefit of the 2300 kg batch is therefore not lower inventory value, but improved powder utilization and fewer batch changes.

Overall, increasing the effective batch size to 2300 kg per machine provides a better balance between powder utilization, traceability, and operational planning. The batch utilization increases to 66.1%, while remaining below the maximum allowed utilization limit of 67%. However, this improvement comes at the cost of higher tied-up capital. The total tied-up capital increases by approximately 11–12% compared with the 2000 kg batch case. Therefore, the 2300 kg batch size is mainly beneficial when improved powder utilization and fewer batch changes are prioritized over minimizing absolute inventory value.

7.4.3 Two Batches can be combined

Another option is to allow controlled mixing between a maximum of two powder batches. In this scenario, remaining powder from one batch may be consolidated with powder from the next batch. This reduces stranded powder inventory and allows the powder to be used more efficiently before it must be removed from operational inventory.

In this scenario, the powder flow is managed within a closed cell consisting of two machines. Two 2000 kg batches may be combined as a powder pool supporting the two-machine cell. With the same batch size as today, the total powder quantity considered in the closed-cell cycle becomes 4000 kg. The maximum allowed powder utilization is 67%. Therefore, the maximum usable powder quantity from the two-batch cycle is 2680 kg.

With an assumed consumption of 95 kg per build, this supports 28 builds, corresponding to a total powder consumption of 2660 kg. This gives a utilization of 66.5%. After 28 builds, the remaining powder inventory is 1340 kg. The remaining powder must then be removed from operational inventory, either as waste or for sell-back to the supplier, unless another approved reuse route is available.

The average powder inventory for this strategy is $(4000+1340)/2 = 2670$ kg, with a tied-up capital of approximately 2 MSEK for the full closed cell. Since the cell contains two machines, the average active tied-up capital per machine becomes 1 MSEK.

Compared with the strict one batch per machine-case, this strategy improves powder utilization and slightly reduces average active tied-up capital per machine. In the two-batch closed-cell case, the same two 2000 kg batches support 28 builds in total, this corresponds to 1 more build per batch. The active tied-up capital per machine is reduced from approximately 1.04 MSEK to 1.00 MSEK, corresponding to a reduction of approximately 3.4%.

The capital-binding reduction is therefore relatively small. The main benefit of this scenario is instead the improved powder utilization. The two-batch closed-cell strategy increases utilization from approximately 61.8% to 66.5%, while remaining below the maximum allowed utilization limit of 67%. It also gives two additional builds from the same total powder quantity compared with two isolated one-batch flows. However, this strategy increases traceability complexity, since the identity and reuse history of both batches must be tracked throughout the combined powder flow.

7.4.4 Fully Flexible Powder Pool, Theoretical best

A final alternative is a fully flexible powder handling strategy. This scenario represents a theoretical best-case from a capital-binding perspective. In this strategy, powder from different batches may be freely mixed, and the powder system is treated as one common operational inventory pool. Exact traceability of the powder mixture is not maintained beyond knowing which batch is added to the system at each refill point.

This means that the system no longer tracks the complete batch composition of the powder in each tank. Instead, traceability is limited to refill history. It is known which batch was added at each point in time, but not the exact batch composition of the powder used in each individual build.

Unlike the previous scenarios, this strategy is not based on consuming a fixed batch before starting the next batch. Instead, powder is replenished continuously based on machine consumption. The machine produces 2 builds per week, and the weekly consumption is 190kg. Since powder is delivered in 100 kg containers, the practical replenishment quantity becomes 200 kg per week per machine. This corresponds to one weekly top-up, which is sufficient to support the weekly production rate.

Table 7-11. Simulation of powder consumption and powder inventory, just in time.

Week	Step	Powder level Tank [kg]	Storage level Batch [kg]	Total Powder [kg]
1	Start fill	1000	0	1000
2	After 2 builds	1000-190=810	200	1010
2	Top up 200 kg	1010	0	1010
3	After 2 builds	1010-190=820	200	1020
3	Top up 200 kg	1020	0	1020
4	After 2 builds	1020-190=830	200	1030
4	Top up 200 kg	1030	0	1030
5	After 2 builds	1030-190=840	200	1040
5	Top up 200 kg	1040	0	1040
6	After 2 builds	1040-190=850	200	1050
6	Top up 200 kg	1050	0	1050
7	After 3 builds	1050-285=765	0	765
8	Top up 200 kg	965	200	965

Table 19 shows a theoretical weekly replenishment pattern where 200 kg of powder is supplied each week while the machine consumes 190 kg. This creates a small surplus of 10 kg per week, causing the total powder level to increase gradually from 1000 kg to 1060 kg over six weeks. In practice, this surplus would need to be managed by occasionally adjusting or skipping a top-up. In the example in Table 7-11, 3 builds are possible and the top up is after 3 builds instead of 2.

The average inventory is calculated as the average powder level during each production interval. Since the top-up steps are only transfers of powder into the tank, they are not treated as separate time periods.

$$((905 \times 2) + (915 \times 2) + (925 \times 2) + (935 \times 2) + (945 \times 2) + (907.5 \times 3)) / 13 = 921 \text{ kg}$$

This means an average tied-up capital of 0.69 MSEK per machine. This represents the lowest active tied-up capital of the evaluated scenarios but requires fully flexible powder mixing and reduced batch-level traceability.

7.4.5 Safety stocks

The previous sections compare the scenarios based on active batch inventory only. However, in practice, additional powder must be held as safety stock to protect production against delivery delays, batch-release delays, and unexpected powder losses. Since the required safety stock depends on the batch strategy, it is evaluated separately in this section. The assumption to calculate this is 1 batch per cell in safety stock to always support a change to a new batch. The numbers can be seen in Table 7-12.

Table 7-12. Safety stocks.

Case	Batch size [kg]	Machines in each cell	Safety stock per machine [kg]	Active powder tied-up capital [MSEK]	Total per machine [MSEK]
7.3.1	2000	1	2000	1.05	2.55
7.3.2	2300	1	2300	1.16	2.89
7.3.3	2000	2	1000	1.00	1.75
7.3.4	200	1	200	0.69	0.84

7.4.6 Powder utilization comparison

Powder utilization is evaluated to compare how efficiently each strategy converts available powder into melted material. In the restricted scenarios, powder that cannot be used further due to operational or traceability constraints is treated as waste or potential sell-back material. The loss value in Table 7-13 is calculated using the full powder price of 750 SEK/kg.

Table 7-13 shows that the strict one-batch-per-machine strategy in 7.3.1 has the lowest utilization, with only 61.8% of the batch melted before the remaining powder must be removed from operational inventory. Increasing the batch size to 2300 kg in 7.3.2 improves utilization to 66.1%, while remaining below the maximum allowed utilization limit of 67%.

The two-batch strategy in 7.3.3 gives the highest utilization among the restricted traceability scenarios, reaching 66.5%. However, because this scenario is based on two 2000 kg batches, the absolute amount of remaining powder is higher, resulting in a larger total loss value. Per machine it is half the value.

The fully flexible powder pool in 7.3.4 represents the theoretical best case. Since powder is continuously replenished and no powder is assumed to become waste due to batch separation rules. This gives the highest theoretical utilization, but also the lowest traceability.

Overall, the results show that increased flexibility in powder handling improves powder utilization and reduces stranded powder. However, this comes with a trade-off: the more flexible the powder strategy becomes, the more difficult it is to maintain detailed batch traceability and material history control.

Table 7-13. Comparison of batch utilization.

Case	Batch size [kg]	Powder melted	Powder waste	Powder utilization %	Loss
7.4.1	2000	1235	765	61.8%	573 750 SEK
7.4.2	2300	1520	780	66.1%	585 000 SEK
7.4.3	4000	2660	1340	66.5%	1 MSEK (2 machines)
7.4.4	Weekly 200 kg flow	200	0*	100%*	0

*The fully flexible powder pool in 7.3.4 is not based on a fixed batch cycle. Powder is replenished continuously and carried forward in the common powder pool. Therefore, no powder is assumed to become waste.

7.4.7 Operational Risks Batch-strategy

In accordance with Lemmens et al. (2022), risk matrices were developed for the different powder handling strategies to determine which strategy poses the lowest risk. Table 7-14 shows the risks associated with the different powder handling strategies, impact values and why they were given that impact value.

Table 7-14. Risk matrix used for evaluation.

Risk	Probability	Impact	Motivation for impact value	Risk Value
Loss of Traceability		5 (Catastrophic)	Critical for quality assurance and certification	
Cross Contamination		5 (Catastrophic)	May affect powder quality, material properties and product performance	
High tied-up capital		4 (Major)	Large financial impact due to expensive powder inventory	
Powder Waste		4 (Major)	Significant material cost losses and reduced sustainability	
Production stops due to Powder Shortages		4 (Major)	Directly affects machine utilization and production output	
Complex Inventory Management		3 (Moderate)	Increases administrative complexity and planning difficulty	
Human Handling Errors		4 (Major)	Can lead to contamination, incorrect handling or safety incidents	

Incorrect refill/top-up operations		5 (Catastrophic)	Wrong powder addition may compromise the entire powder system	
Difficulty scaling the system		3 (Moderate)	Limits future production flexibility and expansion	
Inconsistent powder quality between builds		4 (Major)	Risks unstable process quality and inconsistent product properties	
Total Risk Value				

For the different powder handling strategies increased batch size had the lowest risk and the fully flexible powder pool had the highest, these risk values are displayed in Figure 7-4 (for full risk analysis, see appendix).

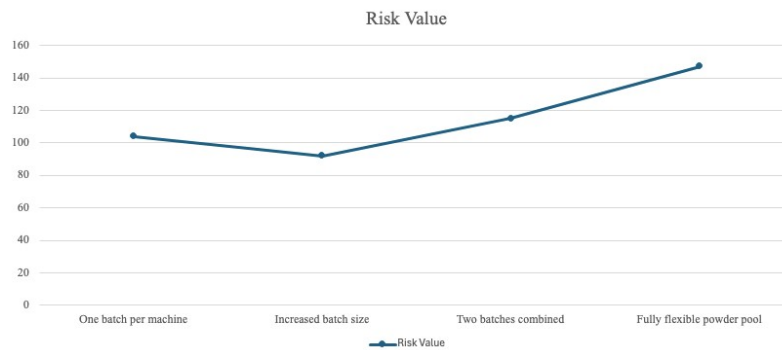


Figure 7-4. Risk Value Comparison.

However, when comparing the powder handling strategies from a broader operational perspective, a clear trade-off can be identified between risk, efficiency and tied-up capital as illustrated in Figure 7-5.

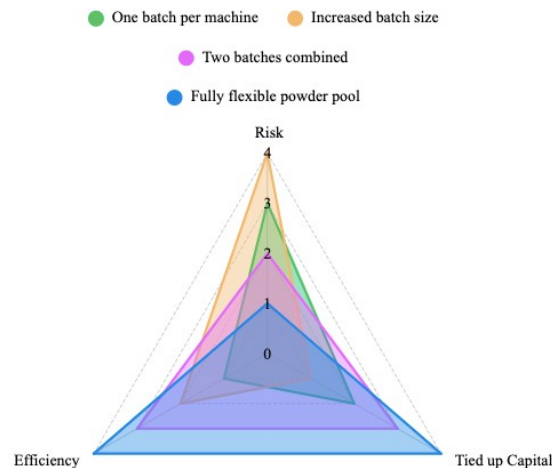


Figure 7-5. Comparison between Risk, Efficiency, and tied-up capital.

The increased batch size strategy represents the lowest-risk alternative by maintaining a highly segregated powder flow while simultaneously reducing the frequency of refill and handling operations. Powder is still maintained within defined batches which preserves strong traceability and minimizes risks related to cross-contamination and inconsistent powder quality. At the same time, the larger batch sizes improve operational efficiency and reduce powder waste generated from repeated material transfers and powder waste. Although the strategy still requires relatively high inventory levels and therefore maintains high tied-up capital, the reduced operational complexity and limited manual handling contribute to a comparatively low overall operational risk. Consequently, the strategy represents a balanced compromise between operational efficiency, process control and material integrity.

The one batch per machine strategy represents the second lowest-risk alternative due to its highly segregated powder flow where each machine operates with a dedicated powder batch. This creates a stable and controlled material flow with strong traceability and low risk of cross-contamination since powder is not shared between systems. However, the strict separation between batches results in high inventory levels and large amounts of unused powder. In addition, the frequent handling and replenishment activities contribute to increased powder waste and operational inefficiencies. Consequently, the strategy prioritizes control, traceability and material integrity over operational flexibility and resource efficiency.

The two batches combined strategy introduces shared use of powder between machines, increasing powder utilization efficiency but reducing the strict segregation between powder lots. As powder is dynamically allocated across multiple processes, risks related to traceability, cross-contamination and inconsistent powder quality increase compared to the more segregated systems. In addition, the higher system complexity requires more coordination and handling steps, increasing the likelihood of human handling errors and incorrect refill operations. At the same time, the strategy improves inventory utilization and reduces tied-up capital compared to the previous alternatives. Overall, this strategy represents a transition toward greater operational flexibility but with increased operational and quality-related risks.

The fully flexible powder pool represents the most integrated and dynamic strategy where all powder is shared freely across machines and batches without strict segregation. This maximizes powder utilization and minimizes tied-up capital by allowing powder to be allocated wherever needed in the system. However, the high degree of integration substantially increases operational risk. Risks related to traceability, cross-contamination and inconsistent powder quality are highest in this strategy due to the continuous mixing and movement of powder throughout the system. Inventory management also becomes significantly more complex due to the reduced visibility of powder history and usage. Although the strategy offers high theoretical scalability and operational flexibility, the increased complexity may limit practical scalability due to reduced process robustness and control.

Overall, the comparison demonstrates a clear trade-off between operational risk, efficiency and tied-up capital. Strategies with stronger segregation provide better traceability, material control and operational robustness but require higher inventory levels and lower operational flexibility. In contrast, more flexible powder handling systems improve powder utilization and capital efficiency, but at the cost of increased complexity and higher operational risk. Table 7-15 provides a summary of how the different strategies perform across the identified risk categories.

Table 7-15. Summary of batch strategies.

Risk Theme	Evaluation Criteria	One Batch per Machine	Increased Batch Size	Two Batches Combined	Fully Flexible Powder Pool
Material Quality & Integrity	Cross-contamination and inconsistent powder quality	Low risk	Low risk	Moderate risk	High risk
Traceability & Inventory Control	Loss of traceability and reduced powder visibility	Low risk	Low risk	Moderate risk	High risk
Supply & Capital Efficiency	High tied-up capital, powder shortages and powder waste	High risk	Moderate-high risk	Moderate risk	Low risk
Operational Execution	Human handling errors and refill/top-up mistakes	Low risk	Low risk	Moderate risk	High risk
Inventory Management Risks	Administrative and operational inventory complexity	Moderate risk	Moderate risk	Moderate-high risk	High risk
Scalability & Flexibility	Difficulty scaling the powder handling system	High risk	Moderate risk	Moderate risk	Low risk
Overall Operational Risk	Combined operational robustness and process stability	Moderate risk	Low risk	Moderate-high risk	High risk

8. Final Concept

This chapter presents the recommended concept for the studied company’s future powder logistics. The concept is an integration of the most efficient and safe solutions identified in the study which include Layout 1, and the use of 100 kg powder containers. It's the last step in the EPL framework and is a combination of the environment, logistic configuration and performance.

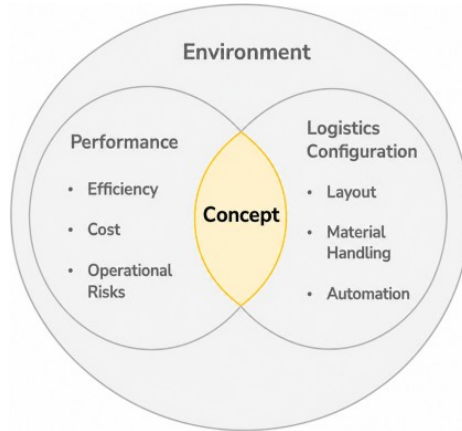


Figure 8-1. EPL Framework, Concept highlighted.

8.1 Detailed Layout

The finalized layout consists of multiple functional zones designed to support the powder-handling process within the future LPBF production environment. The powder area occupies approximately 200 m² and includes five main zones together with a dedicated transport corridor for internal transportation of powder containers, forklifts and AGVs. The finalized layout consists of the zones presented in Table 8-1.

Table 8-1. Zones for Layout.

Zone	Function
A	Inbound/Gods reception + Buffer
B	Virgin Powder Storage
C	Filling station
D	DPS + Powder Control
E	“Bad Powder” Outbound

Zone A functions as the inbound area where incoming powder is received, identified and temporarily buffered before being transferred further into the process. The zone is positioned close to the external “Powder In” entrance and includes goods reception, temporary storage positions and access to both the filling station and virgin powder storage.

Zone B is dedicated to storage of virgin powder containers and includes a Pick-by-Light system used to support operators during material retrieval and identification of powder batches. The zone contains pallet/container storage positions together with direct access to the filling station and LPBF machines. Zone C represents the central powder preparation and filling area where powder is transferred into production tanks before attachment to the LPBF machines. Since the powder containers weigh

approximately 100 kg, the filling station includes an overhead crane solution to support safe handling operations. The zone also contains temporary storage positions for containers during filling operations. Zone D contains the DPS (De-Powdering Station) equipment together with powder-control functions used for powder recovery, inspection and quality verification before reuse in production. The zone also includes temporary storage positions for approved and non-approved powder. Zone E is dedicated to temporary storage and outbound handling of rejected or non-approved powder before disposal or outbound transportation. The area is separated from approved powder handling activities.

Overall, the layout creates a structured powder flow throughout the facility. Powder enters through Zone A, is stored in Zone B, prepared in Zone C and later transferred to Zone D for de-powdering and quality verification after LPBF production. Non-approved powder is finally isolated and transported to Zone E for outbound handling. The complete layout is presented in Figure 8-2.

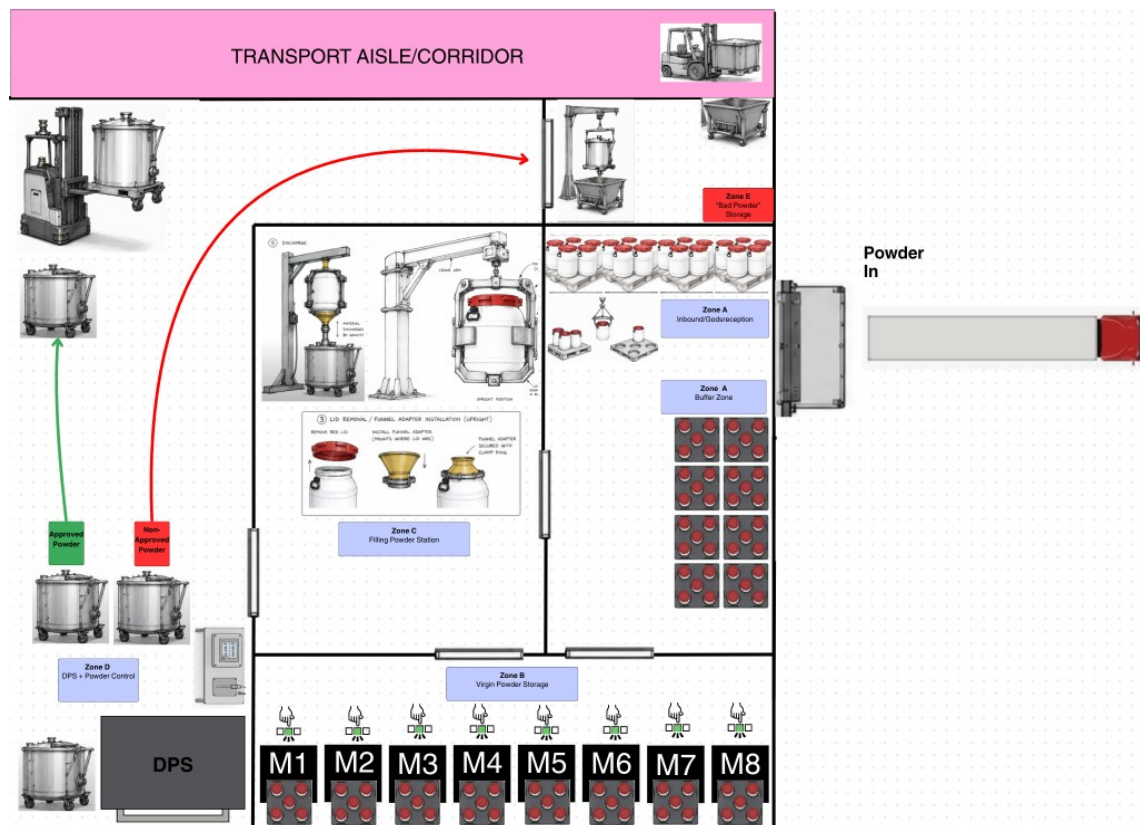


Figure 8-2. Final Concept

8.2 Batch Strategy

The batch strategy affects powder utilization, tied-up capital, storage requirements and traceability. The evaluated strategies should therefore be seen as examples of how different batch rules influence the final concept.

Table 8-2. Batch strategy summary.

Strategy	Powder Utilization	Tied-up-Capital (MSEK/Machine)	Advantage	Disadvantage	Feasible today
One batch per	61.8%	1.05	High traceability, simple quality	Lower batch utilization.	Yes

machine (2000 kg)			assurance, Same as today		
Increased batch size (2400 kg)	66.1%	1.16	Better utilization and fewer batch changes	Higher tied-up capital and larger storage requirement	Yes
Two batches combined (2x2000 kg)	66.5%	1.00	Lower tied-up capital and more flexible powder use	Higher traceability complexity, more production planning needed	No
Fully flexible powder pool	Highest	0.69	Lowest tied-up capital and highest flexibility	Lowest traceability	No, theoretical best

The result shows that strict batch separation provides the highest traceability but also limits how efficiently powder can be used. For example, if one 2000 kg batch is assigned to one machine, the flow becomes simple to control, but remaining powder is locked to that machine. This increases tied-up capital and requires more storage space.

Increasing the batch size, for example to 2400 kg, improves the utilization of each batch and reduces the number of batch changes. However, it also means that more powder is stored in the system at the same time, which increases tied-up capital.

The two-batches-combined strategy shows a possible future improvement. If it is allowed to combine two approved batches in the future, remaining powder could be used more flexibly across machines. This would reduce tied-up capital and make the storage system more efficient. However, since batch mixing is not currently allowed, this cannot be recommended as the initial strategy. It is the same with the theoretical best strategy, which is not currently allowed.

8.3 Automation

The final concept is designed to be automation-ready rather than fully automated from the initial implementation phase. The selected layout includes a dedicated transport corridor for internal movement between powder storage, filling, machine areas and the powder reuse loop. This corridor can be used for manual transport in the short term, while also providing the structure needed for future AGV/AMR-supported transport.

Manual transport is considered the most feasible starting point because it requires a lower initial investment, is less complex to implement and gives flexibility while the high-volume LPBF process is still being established. This is important because the production system is still developing and the final transport frequency, powder movement patterns and operational routines are not yet fully fixed. Starting with manual or semi-manual transport therefore reduces implementation risk while still allowing the new powder-logistics flow to be tested and standardized.

However, the concept should not be designed only for manual handling. As production volume increases, AGV/AMR-supported transport become more relevant because it can reduce operator workload, improve repeatability and support more controlled movement of powder containers and tanks. Automated transport can also improve positioning accuracy at defined pick-up and drop-off points and reduce dependency on operator-controlled movements in high-frequency flows. For this reason, the final

layout should include clear traffic lanes, defined transport positions, sufficient turning space and standardized interfaces between filling and machine areas.

A key requirement for future automation is that the layout does not need to be redesigned when AGV/AMR transport is introduced. The final concept therefore prepares the physical flow for automation, while allowing to implement automation gradually when production volume, investment justification and technical maturity make it suitable. In this way, automation is treated as a future scalability enabler rather than a necessary first step.

8.4 Scalability

A key strength of the final concept is that it is designed as a modular and scalable solution. Rather than being optimized only for a fixed number of machines, the concept is structured around a powder-logistics cell that can be repeated as production volume increases. Each cell contains the key functions needed to support a defined machine group, including powder reception, storage, filling, powder recovery through the DPS, and access to the machine-facing powder storage area. In addition, each cell is connected to a dedicated transport corridor that supports internal material flow.

The scalability of the concept lies in the fact that the same cell structure can be replicated for additional machine groups without changing the underlying powder-logistics logic. As illustrated in Figure 8-3, one cell can support one row of machines, after which additional cells can be added for new rows as the facility expands. In this way, the system can grow from a smaller initial setup to a larger high-volume production environment while maintaining the same operating principles.

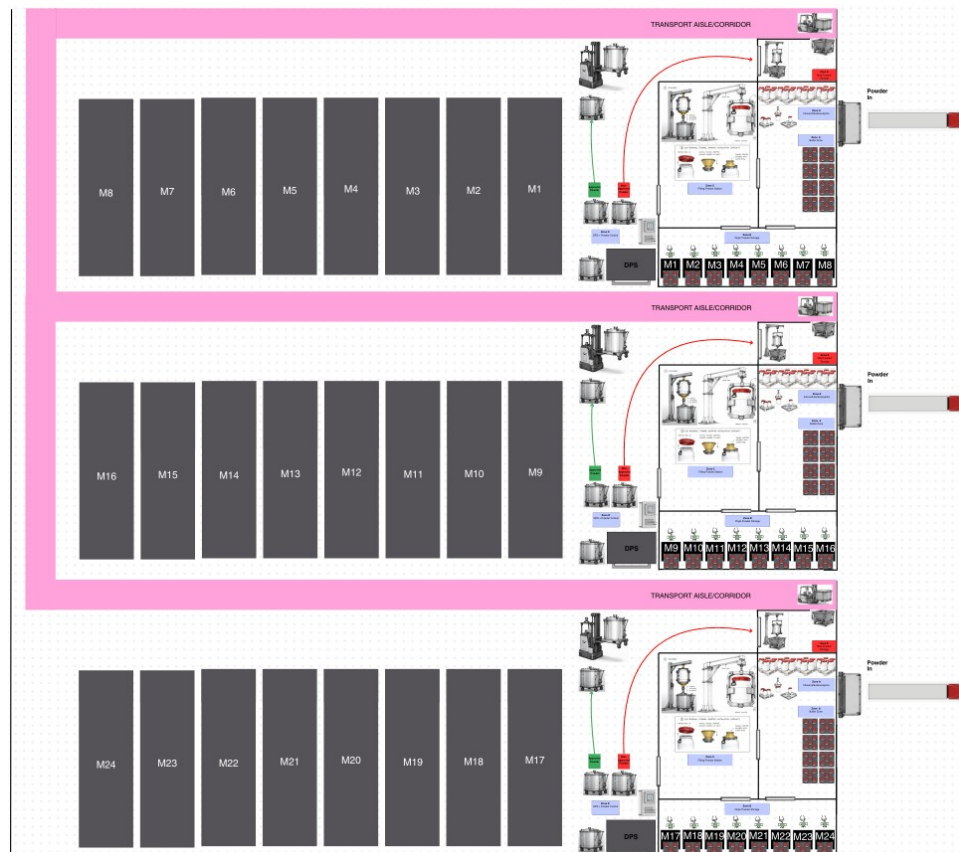


Figure 8-3. Illustration of cells multiplied.

This modular structure supports scalability in several ways. First, it reduces the need for major redesign when production capacity increases, since expansion can take place by adding another standardized cell rather than rebuilding the entire system. Second, it enables a phased implementation where investments can be introduced gradually in line with production growth. Third, it helps preserve traceability, material separation, and standardized work routines, since each new cell follows the same layout logic, storage principles, and flow structure as the previous one.

The repeated cell logic also contributes to operational control. By grouping machines into dedicated powder-logistics cells, transport distances can be kept relatively short, and the relationship between storage, filling, recovery, and machine supply remains clear. This reduces complexity compared with a fully centralized solution serving the entire factory from one single point. At the same time, the concept remains flexible enough to support future automation, since each cell can be designed with the same transport interfaces and corridor structure.

Overall, the concept is scalable because it allows the powder-logistics system to expand in a controlled and standardized way. Instead of designing a unique solution for each stage of growth, the studied company can implement one cell-based concept and multiply it as needed, making the transition to larger production volumes more manageable.

8.5 Current state compared with final concept

To show the effect of the final concept, the current powder-logistics setup was compared with the proposed future concept. The comparison focuses on the main areas where the concept changes how powder is received, stored, handled, transported and controlled. The purpose is not to repeat the full performance analysis from Chapter 7, but to summarize the most important differences between the current low-volume setup and the proposed high-volume powder-logistics concept.

The comparison shows that the final concept mainly improves performance by creating a more structured and controlled flow. The largest measurable improvement comes from replacing 10 kg units with 100 kg containers, combined with a more direct flow into the workshop and defined zones for each powder-related activity. Together, these changes reduce repeated handling and administration activities while improving traceability and scalability.

Table 8-3. Current state compared with final concept.

Area of improvement	Current state	Concept	Difference
Material flow efficiency	Powder handling is mainly manual	Defined zones for every step where powder is involved	More structured flow with fewer unclear handling and storage points
Handling frequency	10 kg units	100 kg units	Reduced handling frequency per kg of powder
Handling activities	72	63	Powder goes directly into workshop
Handling activities per batch	3 210	750	The combination of the three changes above result in 80% less activities for a full batch
Storage	Storage on floor	Controlled storage zones for every different state	Improved separation and clearer material status

Traceability	Relies heavily on manual routines	Barcode/RFID, Pick-by-light and defined storage positions	Stronger connection between batch, container, tank and machine
Filling operation	Dependent on manual handling	Dedicated filling station with lifting support	Safer and more repeatable filling process
Internal transport	Operator-controlled movement	Dedicated transport area prepared for automated transport	Improved flow control and future automation readiness
Operator workload	High dependence on manual handling and operator judgement	More standardized work with lifting support and identification systems	Reduced physical and administrative burden
Scalability	Limited, built for learning	Designed for higher volume, possible to multiply the cell to get more capacity	Much stronger readiness for production scale-up

The comparison shows that the proposed concept creates a clear shift from manual flow toward a standardized and scalable flow. The total number of activities number of activities per full batch is reduced significantly

9. Discussion

This chapter discusses the main findings of the thesis in relation to the aim of developing a safe, traceable, cost-efficient and scalable powder-logistics concept for a future high-volume LPBF production environment. While the performance chapter presents the evaluation of the proposed concept, this chapter reflects on the broader implications of the results and the trade-offs that must be considered when implementing the concept in practice.

The discussion first addresses the contribution of the thesis to the studied company and how the results can support future decisions regarding layout, material handling, batch strategy and automation. Thereafter, the role of automation is discussed, including why automation readiness may be more relevant than full automation in the short term. The chapter also discusses the tension between lean production principles and aerospace requirements, particularly in relation to traceability, safety and controlled material flows. Finally, the sustainability implications, methodological limitations, generalization of the findings and areas for future research are presented.

9.1 Contribution to the Studied Company

This thesis contributes to the studied company by providing a structured decision basis for the future development of powder-logistics in high-volume LPBF production. Since the current powder-logistics setup has mainly been developed for a low-volume and development-oriented environment, the transition to serial production creates a need for more standardized ways of working. The study addresses this by mapping the current process, identifying key constraints and translating them into logistics requirements for the planned production environment.

A central contribution is that the thesis shows how powder-logistics should be treated as an integrated part of the production system rather than as a supporting activity handled separately from layout and production planning. The findings show that decisions regarding powder storage, filling, internal transport, batch strategy and reuse directly affect efficiency, operator safety, traceability and scalability. By connecting these areas in one concept, the study provides the company with a clearer understanding of how powder-logistics decisions influence overall production performance.

The thesis also contributes by highlighting the trade-offs that the company needs to manage when scaling LPBF production. For example, larger powder units and more structured storage can reduce handling frequency and improve efficiency, but also require new equipment, defined storage logic and reliable identification systems. Similarly, more flexible batch strategies can reduce tied-up capital and improve powder utilization but increase the need for robust traceability and quality assurance. These trade-offs are important because the most efficient solution is not necessarily the most suitable solution in an aerospace production context, where safety, contamination control and traceability are mandatory requirements.

Another contribution is the development of an automation-ready logistics concept. The study shows that full automation of the current powder-handling process is not a realistic short-term solution without major changes to how powder is handled. However, by designing the layout with clear transport routes, defined interfaces and standardized load carriers, the company can prepare for future automation while still maintaining a feasible manual solution in the short term. This allows the company to build operational experience and reduce the risk of future redesign when production volumes increase.

Overall, the thesis provides the studied company with a planning-level concept that can support future decisions regarding layout, material handling, powder storage, batch strategy and automation. The contribution is therefore not only the final concept itself, but also a structured way of evaluating powder-logistics alternatives based on efficiency, cost, operational risk, traceability and scalability.

9.2 Automation

Automation emerged as a central theme throughout the study, mainly due to the need to reduce manual powder handling and improve ergonomics, safety and scalability. However, the findings indicate that

full automation may not be the most cost-efficient solution in the early production phase, when volumes and transport frequency are still limited. For this reason, an automation-ready layout may currently be more important than implementing full automation immediately. At the same time, early automation could still be valuable as a learning investment. If the studied company introduces automated transports while volumes are still low, the system can be tested, adjusted and stabilized before production scales up. This could reduce implementation risk later and allow the organization to build knowledge before the logistics flow becomes more demanding. Automation may also reduce the need for local lifting equipment at each machine if tanks can be moved and positioned accurately with an AGV/AMR. Therefore, automation should not only be evaluated based on short-term utilization, but also on its potential to support future scalability, standardization and reduced manual handling.

Overall, the results suggest that the studied company should prepare the layout for automation regardless of when it is implemented. Operator knowledge and flexibility will still be needed for disturbances and unexpected events, meaning that automation should support the powder-logistics system rather than replace operational competence.

9.3 Lean vs Aerospace

The study also revealed an interesting relationship between lean production principles and the realities of aerospace AM. Several lean concepts such as waste reduction, reduced transport distances, minimized handling and improved flow were useful during the logistics analysis. The use of Material Flow Mapping and the HATS framework clearly demonstrated that repeated handling and transportation activities create inefficiencies within powder-logistics. At the same time, the findings indicate that some “non-value-adding” activities may still be necessary within aerospace LPBF production due to strict quality and safety requirements. For example, separated powder batches and extensive traceability procedures may reduce operational efficiency but are necessary to maintain product quality and certification requirements. This creates a situation where the lean objective of minimizing waste must be balanced against aerospace-specific requirements for robustness, redundancy and traceability. The study therefore suggests that lean principles cannot be applied uncritically in aerospace AM environments. Instead, they must be adapted to fit the operational reality and regulatory demands of the industry.

9.4 Sustainability

Sustainability is becoming increasingly important within aerospace manufacturing and additive manufacturing is often associated with improved material utilization and reduced waste compared to traditional manufacturing methods. The findings of this study indicate that powder-logistics design can influence sustainability performance in several ways. More efficient batch strategies and improved powder reuse can reduce material waste and lower the consumption of virgin metal powder. In addition, sustainability is not only environmental, but also social as reduced manual powder handling can improve ergonomics and reduce operator exposure to metal powders. However, sustainability improvements may also involve trade-offs. Increased automation and advanced traceability systems can improve efficiency and reduce waste but also require additional equipment, infrastructure and energy use. Overall, the study suggests that sustainability in future LPBF powder-logistics should be viewed from a broader perspective where environmental, economic and social aspects are balanced together.

9.5 Method

A strength of this study was the combination of interviews, workshops, observations and internal operational data together with Systematic Layout Planning and Material Flow Mapping. This created a structured and systematic approach for both developing and evaluating logistics concepts while also capturing practical operational perspectives from multiple stakeholders. Another strength was the cross-functional involvement throughout the study. By including participants from logistics, production, quality, safety and operations management, the study was able to identify trade-offs and operational constraints that may not have been visible through quantitative analysis alone. This contributed to a more realistic understanding of how the future powder-logistics system may function in practice.

At the same time, the study contains several limitations. Since the future production facility does not yet exist, several assumptions regarding future production volumes and operational conditions had to be made. In addition, the performance analysis was conducted at a conceptual level rather than through simulation or implementation testing. Despite these limitations the study is considered to provide a relevant foundation for continued development of powder-logistics within high-volume LPBF production.

9.6 Generalization and Future Research

Although this study focuses specifically on the studied company and its planned high-volume LPBF facility several findings are likely relevant for other organizations working with metal additive manufacturing. Challenges related to powder handling, traceability, ergonomics, contamination control and scalability are not unique to the studied company but are common issues within industrial LPBF production. Similarly, the need to balance automation, flexibility and operational safety is likely relevant for many future AM facilities. At the same time, aerospace production environments involve particularly strict traceability and certification requirements. This means that some conclusions, especially regarding batch separation and powder traceability may be more restrictive than in less regulated industries.

Several areas for future research were identified during the study. One important area concerns the implementation of automation solutions that can reduce manual operator tasks related to the operator being exposed to powder. Future studies could investigate how automated handling systems can be integrated into LPBF powder-logistics in practice, with the focus on how the filling station can be automated. Another relevant area for future research concerns traceability support systems such as RFID-based tracking and how these technologies could be implemented to support more flexible powder-handling strategies while still meeting aerospace traceability requirements.

Another area for future research is to determine the optimal number of machines that should be included in each powder-logistics cell. In this study, the cell structure is presented as a scalable concept, where the same logistics logic can be repeated as production volume increases. However, the optimal cell size was not evaluated in detail. Future studies could therefore analyze how many machines one cell should support by considering factors such as powder consumption, DPS capacity, filling frequency, transport distances, storage requirements, staffing, and the level of automation.

Future research could also investigate the economic and environmental potential of reusing or selling excess and used powder that can no longer be utilized within aerospace-certified production. This could contribute to improved material utilization and reduced waste within LPBF production systems.

10. Conclusion

This thesis has investigated how powder-logistics can be structured to support the transition from low-volume LPBF production to a future high-volume serial production environment. The study was conducted because scaling LPBF production increases the number of powder movements, handovers, storage needs and traceability requirements, while also increasing the need to control manual handling, operator exposure and tied-up capital. The aim was to support the development of a powder-logistics concept for the studied company's planned high-volume LPBF facility. This was done by mapping the current powder-logistics process, identifying cross-functional requirements and constraints, developing alternative logistics configurations, and evaluating these alternatives in relation to efficiency, cost, tied-up capital and operational risk.

The study shows that the current powder-logistics setup is not suitable for high-volume serial production. The existing system has been developed for a low-volume and development-oriented environment, where powder movements are less frequent and fewer material flows occur in parallel. In a future high-volume environment, this would create challenges related to manual handling, unclear storage logic, traceability, ergonomic strain and scalability. Therefore, powder-logistics must be structured before production is scaled up.

A central conclusion is that the future powder-logistics system should be based on a defined and standardized flow rather than operator-dependent routines. The recommended concept introduces a cell-based layout with defined areas for powder receiving, storage, filling, internal transport and powder recovery. This creates a clearer connection between the physical layout and the operational powder flow. By introducing larger powder units, controlled storage positions, improved identification systems and lifting support, the concept reduces unnecessary handling and creates a more repeatable process.

The material flow analysis shows that the proposed concept can significantly reduce logistics complexity compared with the current state. The main improvement comes from reducing the handling frequency per kilogram of powder and moving powder more directly into the workshop. This reduces the number of handling, administration, transportation and storage activities required in the powder flow. As a result, the concept supports improved efficiency while also reducing the physical and administrative burden on operators.

The study also concludes that batch strategy is a key design decision in high-volume LPBF powder-logistics. Batch strategy directly affects tied-up capital, powder utilization, traceability and operational risk. A strict one-batch-per-machine strategy provides strong traceability and is therefore suitable as an initial implementation approach. However, this strategy also increases tied-up capital and may reduce powder utilization. More flexible strategies, such as allowing two batches to be combined or using a more flexible powder pool, can improve powder utilization and reduce capital binding. However, these alternatives require stronger traceability systems, quality routines and process control. Therefore, the recommended approach is to start with a traceable and operationally robust batch strategy and gradually increase flexibility when the supporting systems and quality requirements allow it.

Automation was identified as an important long-term enabler for scalability, but not as a complete short-term solution. The study indicates that full automation of the current powder-handling process is not currently realistic without major changes to how powder is handled. However, automation can support parts of the logistics system, especially internal material transport. Therefore, the final concept should be automation ready. This means that the layout should include clear transport routes, defined pick-up and drop-off points, standardized load carriers and sufficient space for future AMR or AGV integration. In this way, the company can operate the concept manually in the short term while preparing for future automation as production volumes increase.

Overall, the proposed powder-logistics concept supports the transition from low-volume LPBF production to a more scalable high-volume production environment. The concept improves flow structure, reduces manual handling, strengthens traceability and creates a foundation for future

automation and cell-based expansion. The thesis therefore provides a planning-level decision basis for how powder-logistics can be organized to support safe, traceable, cost-efficient and scalable LPBF production.

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Appendix – Risk matrices

Layout Risks

Risk	Probability	Impact		Risk Value
Layout 1				
Material Flow Congestion	4	4 (Major)	Congestion can reduce throughput, create delays and negatively affect the overall efficiency of the production flow.	16
Cross Contamination	4	5 (Catastrophic)	Cross contamination may compromise powder quality, product integrity and compliance with traceability requirements.	20
Transport Collisions	4	4 (Major)	Collisions involving forklifts, tanks or transport equipment may result in safety incidents, equipment damage and production interruptions.	16
Bottleneck in high-activity areas	5	4 (Major)	Bottlenecks can significantly reduce system capacity and create local overloads that affect multiple connected processes.	20
Long Transport Distances	3	3 (Moderate)	Longer transport routes mainly affect efficiency through increased handling time and transport effort.	9
Poor Traceability	3	5 (Catastrophic)	Inadequate traceability may compromise quality assurance and certification requirements.	15
Limited Scalability	5	3 (Moderate)	Poor scalability restricts future expansion possibilities and reduces long-term system flexibility.	15
Low chance of AGV implementation	4	3 (Moderate)	Reduced compatibility with AGVs mainly affects future automation opportunities rather than current operations.	12
Excessive manual handling	4	4 (Major)	Extensive manual handling increases ergonomic risks, operator dependency and the probability of handling errors.	16
Operator Confusion	3	3 (Moderate)	Unclear workflows or layouts may increase the risk of operational mistakes and reduce process efficiency.	9

Unclear Zoning Boundaries	4	4 (Major)	Poor separation between zones increases the risk of contamination, incorrect material handling and process deviations.	16
Total Risk				164

Risk	Probability	Impact	Motivation for impact value	Risk Value
Layout 2				
Material Flow Congestion	2	4 (Major)	Congestion can reduce throughput, create delays and negatively affect the overall efficiency of the production flow.	8
Cross Contamination	2	5 (Catastrophic)	Cross contamination may compromise powder quality, product integrity and compliance with traceability requirements.	10
Transport Collisions	2	4 (Major)	Collisions involving forklifts, tanks or transport equipment may result in safety incidents, equipment damage and production interruptions.	8
Bottleneck in high-activity areas	2	4 (Major)	Bottlenecks can significantly reduce system capacity and create local overloads that affect multiple connected processes.	8
Long Transport Distances	2	3 (Moderate)	Longer transport routes mainly affect efficiency through increased handling time and transport effort.	6
Poor Traceability	2	5 (Catastrophic)	Inadequate traceability may compromise quality assurance and certification requirements.	10
Limited Scalability	2	3 (Moderate)	Poor scalability restricts future expansion possibilities and reduces long-term system flexibility.	6
Low chance of AGV implementation	1	3 (Moderate)	Reduced compatibility with AGVs mainly affects future automation opportunities rather than current operations.	3
Excessive manual handling	2	4 (Major)	Extensive manual handling increases ergonomic risks, operator dependency and the probability of handling errors.	8

Operator Confusion	2	3 (Moderate)	Unclear workflows or layouts may increase the risk of operational mistakes and reduce process efficiency.	6
Unclear Zoning Boundaries	2	4 (Major)	Poor separation between zones increases the risk of contamination, incorrect material handling and process deviations.	8
Total Risk Value				81

Risk	Probability	Impact	Motivation for impact value	Risk Value
Layout 3				
Material Flow Congestion	3	4 (Major)	Congestion can reduce throughput, create delays and negatively affect the overall efficiency of the production flow.	12
Cross Contamination	2	5 (Catastrophic)	Cross contamination may compromise powder quality, product integrity and compliance with traceability requirements.	10
Transport Collisions	3	4 (Major)	Collisions involving forklifts, tanks or transport equipment may result in safety incidents, equipment damage and production interruptions.	12
Bottleneck in high-activity areas	3	4 (Major)	Bottlenecks can significantly reduce system capacity and create local overloads that affect multiple connected processes.	12
Long Transport Distances	1	3 (Moderate)	Longer transport routes mainly affect efficiency through increased handling time and transport effort.	3
Poor Traceability	2	5 (Catastrophic)	Inadequate traceability may compromise quality assurance and certification requirements.	10
Limited Scalability	2	3 (Moderate)	Poor scalability restricts future expansion possibilities and reduces long-term system flexibility.	6
Low chance of AGV implementation	2	3 (Moderate)	Reduced compatibility with AGVs mainly affects future automation opportunities rather than current operations.	6

Excessive manual handling	1	4 (Major)	Extensive manual handling increases ergonomic risks, operator dependency and the probability of handling errors.	4
Operator Confusion	2	3 (Moderate)	Unclear workflows or layouts may increase the risk of operational mistakes and reduce process efficiency.	6
Unclear Zoning Boundaries	2	4 (Major)	Poor separation between zones increases the risk of contamination, incorrect material handling and process deviations.	8
Total Risk Value				89

Batch Strategy:

Risk	Probability	Impact	Motivation for impact value	Risk Value
One batch per machine				
Loss of Traceability	1	5 (Catastrophic)	Critical for quality assurance and certification	5
Cross Contamination	1	5 (Catastrophic)	May affect powder quality, material properties and product performance	5
High tied-up capital	5	4 (Major)	Large financial impact due to expensive powder inventory	20
Powder Waste	5	4 (Major)	Significant material cost losses and reduced sustainability	20
Production stops due to Powder Shortages	5	4 (Major)	Directly affects machine utilization and production output	20
Complex Inventory Management	3	3 (Moderate)	Increases administrative complexity and planning difficulty	9
Human Handling Errors	2	4 (Major)	Can lead to contamination, incorrect handling or safety incidents	8
Incorrect refill/top-up operations	2	5 (Catastrophic)	Wrong powder addition may compromise the entire powder system	10

Difficulty scaling the system	1	3 (Moderate)	Limits future production flexibility and expansion	3
Inconsistent powder quality between builds	1	4 (Major)	Risks unstable process quality and inconsistent product properties	4
Total Risk Value				104

Risk	Probability	Impact	Motivation for impact value	Risk Value
Increased Batch Size				
Loss of Traceability	1	5 (Catastrophic)	Critical for quality assurance and certification	5
Cross Contamination	1	5 (Catastrophic)	May affect powder quality, material properties and product performance	5
High tied-up capital	5	4 (Major)	Large financial impact due to expensive powder inventory	20
Powder Waste	3	4 (Major)	Significant material cost losses and reduced sustainability	12
Production stops due to Powder Shortages	4	4 (Major)	Directly affects machine utilization and production output	16
Complex Inventory Management	3	3 (Moderate)	Increases administrative complexity and planning difficulty	9
Human Handling Errors	2	4 (Major)	Can lead to contamination, incorrect handling or safety incidents	8
Incorrect refill/top-up operations	2	5 (Catastrophic)	Wrong powder addition may compromise the entire powder system	10
Difficulty scaling the system	1	3 (Moderate)	Limits future production flexibility and expansion	3
Inconsistent powder quality between builds	1	4 (Major)	Risks unstable process quality and inconsistent product properties	4
Total Risk Value				92

Risk	Probability	Impact	Motivation for impact value	Risk Value
Two Batches Combined				
Loss of Traceability	3	5 (Catastrophic)	Critical for quality assurance and certification	15
Cross Contamination	3	5 (Catastrophic)	May affect powder quality, material properties and product performance	15
High tied-up capital	3	4 (Major)	Large financial impact due to expensive powder inventory	12
Powder Waste	2	4 (Major)	Significant material cost losses and reduced sustainability	8
Production stops due to Powder Shortages	3	4 (Major)	Directly affects machine utilization and production output	12
Complex Inventory Management	4	3 (Moderate)	Increases administrative complexity and planning difficulty	12
Human Handling Errors	3	4 (Major)	Can lead to contamination, incorrect handling or safety incidents	12
Incorrect refill/top-up operations	3	5 (Catastrophic)	Wrong powder addition may compromise the entire powder system	15
Difficulty scaling the system	2	3 (Moderate)	Limits future production flexibility and expansion	6
Inconsistent powder quality between builds	2	4 (Major)	Risks unstable process quality and inconsistent product properties	8
Total Risk Value				115

Risk	Probability	Impact	Motivation for impact value	Risk Value
Fully Flexible Powder Pool				
Loss of Traceability	5	5 (Catastrophic)	Critical for quality assurance and certification	25

Cross Contamination	5	5 (Catastrophic)	May affect powder quality, material properties and product performance	25
High tied-up capital	1	4 (Major)	Large financial impact due to expensive powder inventory	4
Powder Waste	1	4 (Major)	Significant material cost losses and reduced sustainability	4
Production stops due to Powder Shortages	2	4 (Major)	Directly affects machine utilization and production output	8
Complex Inventory Management	5	3 (Moderate)	Increases administrative complexity and planning difficulty	15
Human Handling Errors	4	4 (Major)	Can lead to contamination, incorrect handling or safety incidents	16
Incorrect refill/top-up operations	5	5 (Catastrophic)	Wrong powder addition may compromise the entire powder system	25
Difficulty scaling the system	3	3 (Moderate)	Limits future production flexibility and expansion	9
Inconsistent powder quality between builds	4	4 (Major)	Risks unstable process quality and inconsistent product properties	16
Total Risk Value				147

Risk	Probability	Impact	Motivation for impact value	Risk Value
Forklifts				
Collisions/Accidents	4	5 (Catastrophic)	Can cause injuries and production stoppages	20
Human handling errors	4	4 (Major)	Can lead to contamination, incorrect handling or safety incidents	16
Production interruption	3	4 (Major)	Negative impact on efficiency and overall productivity	12
Flexibility limitations	2	3 (Moderate)	Can restrict adaptability in production and reduce operational efficiency	6

Implementation complexity	1	4 (Major)	May increase deployment time and require additional resources	4
Safety risk (operator injury)	4	5 (Catastrophic)	High risk of serious injury in case of misuse or incidents	20
System reliability	3	3 (Moderate)	May cause operational disturbances and affect system stability	9
Total Risk Value				87

Risk	Probability	Impact	Motivation for impact value	Risk Value
Cranes				
Collisions/Accidents	2	5 (Catastrophic)	Can cause injuries and production stoppages	10
Human handling errors	2	4 (Major)	Can lead to contamination, incorrect handling or safety incidents	8
Production interruption	2	4 (Major)	Negative impact on efficiency and overall productivity	8
Flexibility limitations	3	3 (Moderate)	Can restrict adaptability in production and reduce operational efficiency	9
Implementation complexity	3	4 (Major)	May increase deployment time and require additional resources	12
Safety risk (operator injury)	2	5 (Catastrophic)	High risk of serious injury in case of misuse or incidents	10
System reliability	2	3 (Moderate)	May cause operational disturbances and affect system stability	6
Total Risk Value				63

Risk	Probability	Impact	Motivation for impact value	Risk Value
AGVs				
Collisions/Accidents	3	5 (Catastrophic)	Can cause injuries and production stoppages	15

Human handling errors	1	4 (Major)	Can lead to contamination, incorrect handling or safety incidents	4
Production interruption	2	4 (Major)	Negative impact on efficiency and overall productivity	8
Flexibility limitations	1	3 (Moderate)	Can restrict adaptability in production and reduce operational efficiency	3
Implementation complexity	5	4 (Major)	May increase deployment time and require additional resources	20
Safety risk (operator injury)	1	5 (Catastrophic)	High risk of serious injury in case of misuse or incidents	5
System reliability	3	3 (Moderate)	May cause operational disturbances and affect system stability	9
Total Risk Value				64

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