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Pull System in Lean Production: a critical analysis of parameters influencing kanban sizing

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To my Mom and Dad, who
have always supported me
with constant effort and
belief in my potential.

Abstract

This master's thesis investigates a new approach of pull systems sizing in lean manufacturing, focusing on two key applications: purchasing and production.

The traditional formula for pull system dimensioning, while widely used, often lacks precision due to the many factors influencing stock levels and consumption trends. Through an internship in auxiell Spa, a consultancy firm specializing in lean transformations, this project aimed to address these challenges by developing a more accurate method.

The new formula was designed to adapt to real-world variables affecting both purchasing and manufacturing environments. After initial testing in Excel to simulate stock trends, the analysis was extended and refined in Python, allowing for a more comprehensive evaluation across larger datasets. The comparative analysis between the traditional and new formulas demonstrated significant improvements in reducing average stock levels, lowering inventory costs, and enhancing system efficiency.

Moreover, it provides valuable insights by offering a flexible framework that can be applied to various real-world scenarios. The new formula allows users to explore key factors such as order frequency, supplier lead times, and service levels. By adjusting variables, the formula can be customized to suit different production or purchasing environments, making it a versatile tool for improving inventory management.

This analysis aims to minimize stock levels while maximizing service levels, as well as to identify common patterns that could be useful for improving value delivery in other clients or situations. Additionally, the model helps highlight both qualitative and quantitative benefits compared to the traditional formula.

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1 Introduction

Meeting market demand has always been a crucial challenge for companies striving to stay relevant. Historically, the customer wasn't always the main focus. In the beginning, companies would push their products onto the market, expecting customers to adapt to what was available. But as years went by and technology advanced, customers' needs became more complex and specific, leading to a complete shift in this approach. This evolution in customer expectations drove the transformation of production systems, ultimately giving rise to lean management a streamlined, flexible approach rooted in solid principles that prioritize the customer, aiming to deliver the maximum value they seek.

This master thesis presents a detailed project focused on analyzing the parameters for pull system sizing. During my internship in auxiell Spa, a consultancy firm in Padua specialized in lean transformation, I explored the complexities involved in correctly sizing a pull system. While auxiell has extensive experience in guiding companies through process improvements, they recognized that traditional methods for dimensioning pull systems often lack accuracy due to the many variables that affect the calculations in real life.

In my analysis, I introduced a new concept of pull system sizing, applied in two different areas: purchasing and manufacturing. Both areas share a common foundation, but each has specific variables that characterize the approach. To better understand the formula's effectiveness in kanban sizing, I initially conducted an analysis using Excel to simulate stock levels and consumption trends. Later, this approach was refined by transitioning to Python, a more advanced tool that allowed for the analysis of large datasets, providing insights on multiple items at once.

This thesis compares the traditional formula with the new approach, offering a deeper understanding of how to adjust pull system sizing based on different scenarios. By doing so, the system can reduce average stock levels and lower overall inventory costs. Additionally, this approach enhances system efficiency, helping to create a more responsive and streamlined inventory process that benefits businesses both in terms of cost savings and operational effectiveness.

2 The Lean Philosophy

In today's fast-changing world of technology, companies are always trying to keep up with the latest trends. But in their rush to be up to date, they often forget about the basics: having solid, reliable processes in place. Without these strong foundations, trying to introduce new technologies can lead to all sorts of problems, from confusion and inefficiency to missed opportunities. Interestingly, a philosophy that emerged back in the 1950s offers a solution that's still incredibly relevant today.

This philosophy is called Lean, and it was developed by Toyota. The whole idea behind Lean is to do more with less, getting the most value while wasting as little as possible. It's not just about cutting costs; it's about making every part of production and management as efficient as it can be. Lean is all about continuous improvement and making the best use of whatever resources you have. By getting rid of waste (which the Japanese call 'Muda'), reducing inconsistencies ('Mura'), and avoiding overburden ('Muri'), companies can not only become more competitive but also create a culture where improvement never stops.

What's really interesting is that Lean principles have spread far beyond manufacturing. They're now being used in everything from healthcare to software development. Many organizations are on what's known as a Lean transformation journey. This isn't just about quick fixes; it's about making long-term improvements that stick. Companies that embrace Lean are better equipped to adapt to new technologies because their processes are designed to be flexible and resilient.

The goal of this chapter is to provide an overview of the Lean concept, beginning with its theoretical definition and historical origins. Following this, it will explore the auxilliary Lean System, outlining its seven principles.

2.1 Introduction to Lean production

Lean thinking is a business philosophy, which based its fundamentals in the Toyota production system invented by Taiichi Ohno¹ to improve performance with efficient resource utilization: it indicates how to do more with less, striving for produce only what customers really need.

¹ Taiichi Ohno (1912-1990) was a mechanical engineer and the inventor of the Toyota Production System (TPS), also known as Lean production. He began his career at the Toyoda family's textile factory before transitioning to the automotive industry in 1939. There, he became a member of the executive council at Toyota.

Lean thinking emphasizes the concepts of effectiveness and efficiency, often summarized as "doing more with less." Additionally, it represents a method that enhances job satisfaction by involving individual operators directly in the process. The transformation of muda² into value is immediate, ensuring that employees see the impact of their efforts firsthand.

Lean thinking provides a way to specify value, align value-creating activities in the best sequence, carry them out without interruption when someone requests them, and perform them more effectively. (Womak & Jones, 1996)

Taking a step back, the origins of Lean philosophy can be traced directly to the evolution of mass production. At the beginning of the 20th century, societal habits shifted due to improved living standards and a growing global population. These changes rendered the traditional hand-crafted production system inefficient, as it could not meet the rising market demand. In response, the USA introduced mass production, built on three fundamental principles.

- The first principle refers to the scientific analysis pioneered by Frederick Taylor, a key figure in industrial engineering. In his 1911 studies, Taylor emphasized the necessity of measuring workers' performance through the analysis of times and methods for each operation. The aim of these measurements was to establish the "one best way" to perform a task, ensuring efficiency and consistency.
- The second principle of mass production is the continuous flow in the assembly line, introduced by Henry Ford, the founder of the famous automotive company. Ford revolutionized the supply chain with the production of the Model T, the first car designed for mass production. In this system, the materials move along the supply chain, bringing components to stationary workers. To facilitate this, Ford introduced standardization of components, making production simpler, and developed the bill of materials, a document detailing every component required to produce a finished product.
- The third principle is based on economies of scale: as production volumes increase, the average unit cost decreases, meaning the cost of producing each individual unit becomes lower. This concept applies to all production systems but is especially significant in mass production, which focuses on reducing a specific fixed cost: the setup cost. By spreading this cost over a larger production volume, it encourages the production of as many units as possible. (Pavanato, 2020)

² Muda is a Japanese word that means waste. In the Lean philosophy refers to activities that doesn't create any value to the process.

Mass production experienced significant development during World War II, pulled by the huge demand for goods, the need for standardization, and the requirement for quick market response. It became the benchmark for production systems.

Years later, in the post-war period, the global situation had shifted significantly. In Japan, the aftermath of the atomic bombings had created a unique environment. The market demands were limited and unpredictable. Within this context, the Toyota Production System (TPS) was developed to address the low demand for goods and to optimize the use of scarce resources. TPS also embraced the Japanese cultural emphasis on people’s involvement and teamwork, characteristics that were vital in the post-war recovery.

Table 2-1 Differences between Mass production and TPS (Pavanato, 2020)

	Mass production	TPS
Stocks	High	Low
Flexibility mix: ability to change quickly the type of products at a low cost	Low	High
Machines saturation	High	Low
Production time	High	Low
Spaces	High	Low
Wastes	High	Low
Versatility of operators	Low	High

In essence, the history of Lean philosophy is a testament to its necessity and effectiveness. It was born out of a need to overcome inefficiencies and respond to dynamic market conditions, particularly in post-war Japan. This context underscores the importance of Lean thinking in modern production systems, where it continues to drive performance improvements and resource optimization.

2.2 Introduction to auxiell lean system

Auxiell³ Spa is a consultancy firm based in Padua, dedicated to guiding companies on their lean transformation journey. The company analyzes, designs, implements, and measures processes to

³ Auxiell Spa is the company that host me during my internship with the objective of writing the master thesis and the possibility to physically see in-progress lean transformation companies. For this reason, I mentioned the auxiell lean system and explained the company approach.

ensure they are effective and efficient, supporting sustainable business models and fostering systematic evolution through tangible, quantifiable results (auxiell, 2023). Founded in 2005 in collaboration with Unox, a leader in professional oven production and a global example of complete lean transformation. Auxiell Spa currently employs approximately 100 people across its two offices in Padua and San Luis Potosí, Mexico.

The success of auxiell Spa has been defined by its resolute commitment to substantiating the efficacy of lean transformation through concrete results, underscoring the crucial difference between "implementing lean" and "being lean." Understanding, internalizing, and effectively applying lean principles are therefore essential for achieving success. Pursuing transformation without clear goals and guidelines is impractical; however, when a unified lean culture is embraced company-wide, attaining objectives becomes more achievable, expedient, and sustainable.

The auxiell Lean System is structured with a foundation of seven principles, the pillars, which support the methods and techniques to follow for a structured and scientific approach to all activities. These activities use different tools depending on the area in which they are applied.

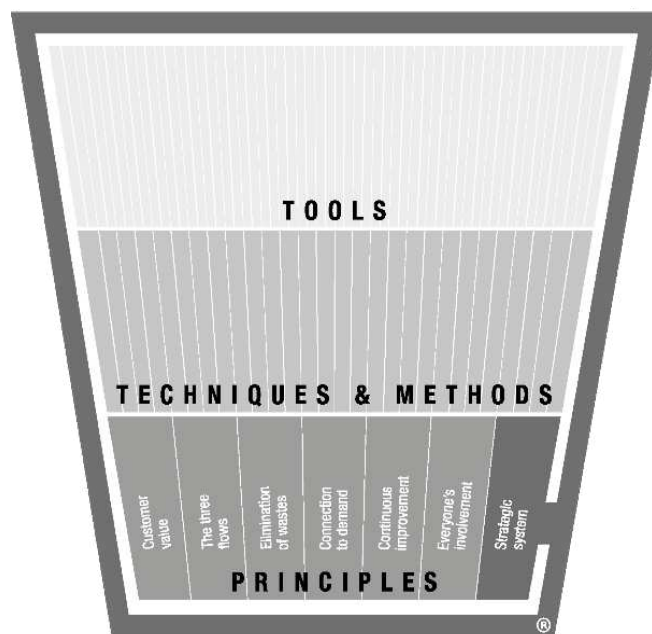


Fig. 2-1 Auxiell lean system

Listed below are the seven principles of the auxiell lean system (auxiell, 2023).

2.2.1 Customer value

The first principle of the auxiell Lean system is to define value for the customer. Value is defined as “everything for which the customer would be willing to pay”, or as the benefit, interest, utility, or compensation that stakeholders receive from their contributions to the company. It's crucial to note the role of the verb "would be" in the previous statement, as customers often aren't aware of the product or service's production process and simply pay to receive it. If the production process were scrutinized, imperfections and waste that customers wouldn't find acceptable could be identified. To clarify this point, consider a famous quote from Shigeo Shingo: "When you buy a banana, all you want is the fruit, not the skin, yet you pay for both. It's wasteful, and customers shouldn't have to pay for waste" (Shingo, 1987). Clearly, the banana skin doesn't represent "value" for the customer since it's thrown away once the fruit is consumed, resulting in waste. This concept can easily be applied to observing a process and visualizing its activities.

A process can be summarized into four fundamental activities:

- Processing: altering form or substance, assembling or disassembling;
- Transportation: changing location;
- Inspection: comparing against a standard;
- Waiting: time intervals without processing, transportation, or inspection.

Only processing activities represent "value" for the customer, and only for these activities would they be willing to pay; other activities should be eliminated or significantly reduced where possible.

Another way to define value is to consider it as the ratio between benefits and costs for the customer. Benefits aren't solely economic; they can also be assessed from personal, social, psychological, or other perspectives to gain a comprehensive view of value (Pavanato, 2020). Therefore, defining value for the customer forms the foundation upon which work is developed: the ability to understand customer needs and intervene effectively in processes to improve them.

2.2.2 Three flows

The second principle of the auxiell Lean System is the three flows of value. Before going into the various flows and their peculiarities, it is essential to define the concept of a process: it is a set of operations or phases that, through transforming resources and resources to be transformed (materials, information, or people), convert an input into an output. Similarly, an operation is

defined as a basic unit of work that changes the state or position of a material object, immaterial object, or person in space. Each process can be defined through five different components (known as 4M+E): men (people), materials, machines, methods, and the environment in which it operates.

Traditional companies are typically organized functionally along hierarchical lines, structured by conceptually and sometimes physically separated departments that create interfaces blocking the flow of materials, information, and people. This principle highlights the fundamental importance of facilitating the flow of these streams by eliminating or severely limiting the presence of any kind of ideal or physical obstacle. Within a process, three types of flows can be identified:

- **Operational flow:** the sequence of operations that transform resources from input into output.
- **Information flow:** the set of informational standards aimed at enabling the operational flow.
- **Workflow:** the combined work of transforming resources (people and machines) that drives the operational and information flows.

All these contribute together to define the process as a whole. Value is generated in the operational flow, making it crucial to start from this flow to redesign processes, eliminate all obstacles, and ensure the flow of streams using the correct resources. The flow of value must be maintained through continuous movement in time and space; any halt in this flow exposes waste (auxiell, 2023).

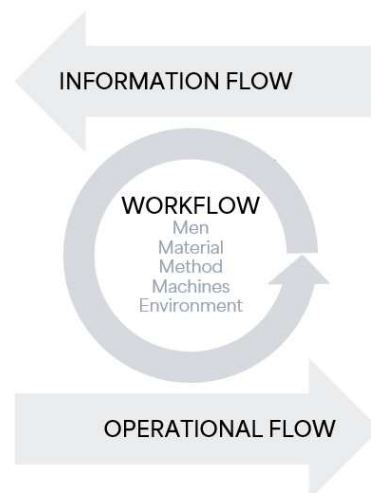


Fig. 2-2 Visual representation of three flows of value

The flow of these three streams, particularly the operational flow, is influenced by three defined factors:

- *Muda* (waste): These will be described further in the explanation of the next principle.
- *Mura* (irregularities): Considered the root cause of all wastes as it leads to the generation of muda and muri. It can be caused by:
 - Fluctuations in demand
 - Lack of quality
 - Lack of standardization
- *Muri* (overload): refers to overburdening workers, machines, or processes. When too much is expected from them, it causes strain, leading to breakdowns, mistakes, and reduced efficiency.

By eliminating mura, it is possible to build stable production systems with constant process parameters over time, thus facilitating the flow of value to the customer.

2.2.3 Eliminating waste

The third principle of the auxiell Lean System is the elimination of waste, known as muda, within processes. By carefully analyzing each process, two types of activities can be identified:

- **Value-added activities:** these are operations that create perceived value for the customer, such as processing activities.
- **Non-value-added activities:** these are operations that do not create perceived value for the customer. They can be classified as:
 - Type 1 Non-value-added activities: activities within the process that cannot be immediately eliminated due to physical, legal, administrative, technological constraints, or requiring significant investments.
 - Type 2 Non-value-added activities: activities within the process that can be immediately eliminated.

Waste activities are precisely non-value-added activities and, in accordance with the first principle, they must be eliminated to generate value exclusively for the customer. The seven wastes defined by Taiichi Ohno, and incorporated into the auxiell Spa system are:

- **Overproduction:** producing more than is required by the next process step or before actual demand, considered the root cause of all wastes.
- **Waiting:** idle time of transforming or transformed resources. Waiting times for transforming resources can result from internal or external delays, batch production, and material synchronization. Waiting times for transformed resources are generally influenced by activity planning and scheduling.
- **Transportation:** any movement of transformed resources that does not add value for the customer.
- **Incorrect Processes:** inefficient process phases or operations due to inefficiencies in transforming resources or product/process design.
- **Inventory:** accumulation of transforming, in-process, or transformed resources. Besides being a waste itself, it leads to other issues by hiding problems that could otherwise be identified and eliminated.
- **Motion:** any non-value-added movement by the workflow, i.e., transforming resources.
- **Defects:** production of defective outputs that do not meet customer requirements or product/service specifications. This waste results in rework or scrap, consuming additional resources.

An eighth waste can also be identified: it encompasses a broad concept that can be summarized, even if it is not exhaustively, as the waste of intellect. This muda refers to the underutilization of an individual's energy, communication, knowledge, and creativity, intrinsic qualities that are not adequately and effectively utilized (Pavanato, 2020).

As evident, all these wastes are interconnected, and the presence of one often leads to the generation of related wastes. Therefore, it is crucial to identify the root cause generating them and take action to remove them from processes, thereby promoting process improvement.

2.2.4 Connection to demand

The fourth principle of the auxiell Lean System is demand alignment. Any process only makes sense when there is a demand to satisfy, meaning the request for goods, services, or a mix of both in the local or global market, along with a readiness to pay the appropriate price per unit.

Aligning with demand entails adapting processes to meet customer requirements and ensure the fulfillment of desired outputs. The key objective is to pull production from the market by producing only what is truly necessary and wanted by the customer, thus avoiding resource waste.

Driving processes based on customer demand involves:

- Efficient demand transmission, ensuring clear, correct, complete, and timely communication of customer-defined value information throughout the process phases.
- Demand transmission is sometimes challenging due to two main factors: (auxiell, 2023)
 - Information asymmetry: differential access and knowledge of customer or supplier information, often leading to erroneous assumptions. This is associated with the well-known "bullwhip effect" where slight upstream variations cause significant downstream impacts due to information sharing discrepancies.



Fig. 2-3 Bullwhip effect

- Market variability: continuous changes in customer demands influenced by market evolution, a factor that cannot be eliminated but can be controlled to mitigate its effects.

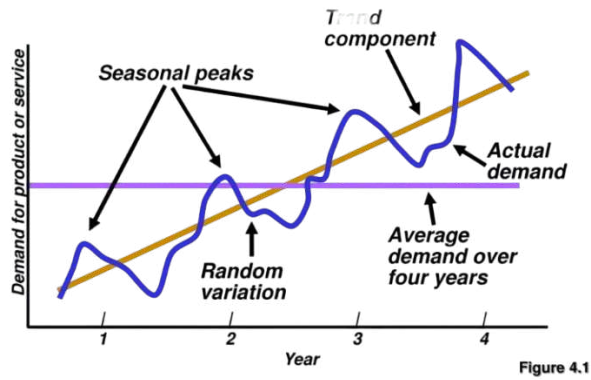


Fig. 2-4 Components of market demand (Lombardi, 2008)

Inefficient demand transmission results in resource accumulation and imbalances in transforming resources, contributing to the creation of many of the wastes mentioned earlier.

Evaluation of demand alignment and process redesign are achieved using specific metrics such as:

- **Takt Time:** the pace of customer demand, defined as:

$$Takt\ time = \frac{Available\ time\ in\ a\ defined\ period}{Customer\ demand\ the\ defined\ period}$$

- **Cycle Time:** the interval between the output of two products from the process, considering only processing activities.
- **Processing Time:** the actual time taken to process a product if done continuously by a single resource throughout the process, without interruptions.
- **Lead Time:** the total time for an output to be produced from the process.

2.2.5 Continuous improvement

The fifth principle of the auxiell Lean System is continuous improvement. Lean thinking is based on the pursuit of perfection, an ideal and flawless condition that can never truly be achieved but is essential to strive towards for constant improvement. Improvement can be pursued through different strategies over various timeframes, including:

- **Kaizen:** Short-term or daily improvements aiming for continuous and incremental enhancements on processes that remain structurally the same.

- ***Kaikaku***: Medium-term improvements (weeks or months) focusing on radical and sudden process improvements through short-term projects (Kaizen events), aiming to create a break from the past.
- ***Kakushin***: Long-term improvements (years) through innovation and strategic selection.

All these improvement types are crucial for moving towards perfection, with Kaizen particularly embodying the concept of true continuous improvement. It involves slow, steady, and relentless progress that builds on the past to improve the present and future. This approach is facilitated through the SPDCA method (Scan – Plan – Do – Check – Act), auxiell Spa's refined version of the Deming Cycle. This scientific method consists of five phases:

1. **Scan**: Analyze the context to define the current state, identify existing wastes, and pinpoint improvement opportunities.
2. **Plan**: Seek root causes, design countermeasures, define metrics and goals, and plan improvements using the 5W2H approach (what – where – when – who – why – how – how much).
3. **Do**: Execute planned activities and corrective actions consistently with the action plan from the previous phase.
4. **Check**: Verify that activities were carried out according to the action plan, monitor and measure results achieved against set objectives. If results fall short, restart from phase 1 (Scan) to initiate an iterative process.
5. **Act**: Consolidate and standardize the new method, apply it to processes that will benefit. This phase is crucial for embedding the improvement achieved (auxiell, 2023).

The focus in the final phase of the SPDCA cycle is crucial: creating a new standard ensures a stable base for future improvements without reverting to previous states. The concept of a standard, according to lean thinking, is defined as “the best current practice to achieve desired process outputs with maximum quality and minimal resource consumption”. Standards are flexible ideas meant to evolve but play a critical role in measuring process status and driving improvements. As paraphrased from Lord William Thomson Kelvin (1824 – 1907), a British physicist and engineer, if something cannot be measured, it cannot be improved.

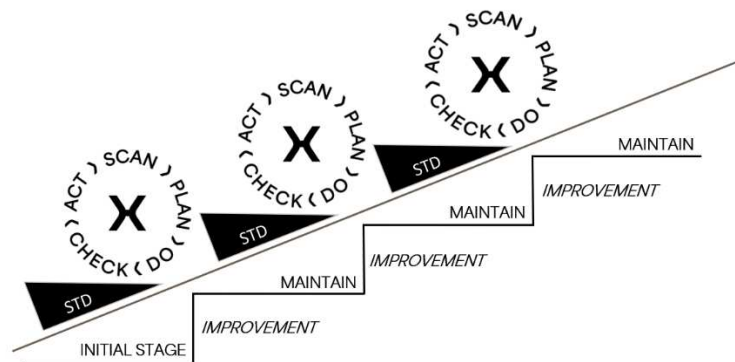


Fig. 2-5 SPDCA cycle designed by auxiell Spa

2.2.6 Everyone's involvement

The sixth principle of the auxiell Lean System is involvement of everyone. Lean thinking eliminates distinctions between thinkers and doers, decision-makers and implementers, by placing all on an equal footing and fostering communication among different parts of the organization. *Gemba*, the physical place where processing activities occur, serves as the meeting point between management and operational parts of the company, rejecting hierarchical structures and confined departments. Involving everyone entails forming cross-functional teams capable of problem-solving, leveraging the collaboration of individuals with diverse backgrounds to swiftly identify root causes of issues. Engaging people means providing them with support and challenges that match their skills, avoiding situations that are hard to manage and maximizing their growth potential.

It is logical to emphasize the critical role that support plays in an individual's career, as its absence, coupled with more or less challenging tasks, can lead to withdrawal or complete disengagement. This results in the loss of their contribution and potential shifts in their attitude towards the company itself (Pavanato, 2020). Each individual has the capacity to add value to their workplace through knowledge, skills, and behaviors that they themselves should highlight and the company should nurture.

The Lean system as a whole requires cultural change across every component of the organization, fostering new motivations and driving continuous improvement through the involvement of every individual.

2.2.7 Strategic system

The seventh principle of the auxiell Lean System is strategic alignment. This principle emphasizes that simply applying lean techniques and methods is not enough to truly improve an organization. It is essential to "be lean" in order to achieve valid and lasting results that fundamentally change a company's processes. "Being lean" means approaching everyday operations with the scientific and systemic perspective of the SPDCA method, using and applying suitable principles, techniques, and tools. Change must be initiated promptly, progressively involving all processes and aligning them with each other, ultimately aligning their overall direction with the company's strategies. This approach guides the entire organization in the right direction, involving every individual in defining and executing the process of change and strategic implementation (auxiell, 2023).

Therefore, the strategic system aims to manage internal company projects so that each effort closes the gap between the current situation and the defined master direction at the strategic level.

3 Principle #4 – Connection to demand

This chapter focuses on the fourth principle of the auxiell Lean System: connection to demand. We will explore how aligning processes with market demand optimizes production and meets customer needs.

Demand alignment means that processes are only justified by actual market demand for products or services. This principle emphasizes adapting processes to meet customer needs, ensuring production is necessary and desired, and avoiding waste. This process is divided into two essential actions: understanding market demand and realizing market demand. Understanding market demand involves interpreting and communicating demand throughout the entire process. Realizing market demand means designing and creating a process capable of generating the desired output.

Below, we will start by analyzing market demand and then examine the differences between push and pull production systems. Next, we will discuss metrics to evaluate market demand alignment and conclude with the kanban system.

3.1 Understanding market demand

The first step is sometimes forgotten, but it is fundamental. If information are not shared along the entire process generate misunderstandings that turn into muda. The characteristics that composed the information are four: completeness, clarity, correctness, timeliness (Pavanato, 2020):

- **Completeness:** quantities, timelines, costs must be precise
- **Clarity:** the information must be understandable by every transforming resources
- **Correctness:** information must be aligned with customer needs
- **Timeliness:** the market demand must be shared within the time needed to satisfy the demand

However, market demand is not always transmitted completely, clearly, correctly, or timely. Why does this happen? Market demand includes both predictable and unpredictable factors. The latter introduces uncertainties, making accurate predictions challenging. Methods like statistical models, market research, historical data analysis, and machine learning algorithms help estimate demand, but these methods cannot account for all unpredictable events. Factors affecting market demand include (Krajewski, et al., 2015)

- **Seasonality:** Certain products may have fluctuating demand based on the season or time of year.
- **Economic Conditions:** Economic growth or recession can impact consumers' purchasing power and demand for products.
- **Consumer Trends:** Changes in consumer preferences and trends can lead to shifts in demand
- **Competitive Actions:** Competitors' activities, such as new product launches or promotions, can affect market demand
- **Regulatory Changes:** New regulations or changes in existing laws can impact the demand for specific products

In conclusion, understanding and addressing these factors is essential for aligning production with market demand. Effective communication and adaptation to demand fluctuations are key to optimizing production processes. In the following sections, we will explore the concepts of push and pull production systems, examining how they relate to demand alignment and their impact on production efficiency.

3.2 Push

As the name suggests, push production means “pushing” production through the supply chain based on forecasted demand. This method relies on predicting future customer demand and planning production accordingly. A familiar example of push production is seen at McDonald's. During peak hours, McDonald's predicts demand based on customer trends and produces a certain number of popular items in advance. They use visual aids, like slides, to manage inventory and ensure a smooth flow of products, similar to a FIFO (First In, First Out) line. The goal is to have products ready when customers arrive, allowing the restaurant to serve as many people as quickly as possible. However, this approach carries risks. If fewer customers than anticipated show up, excess products may become waste.



Fig. 3-1 McDonald's buffer of burgers

Despite its efficiency during high-demand periods, push production can lead to significant waste if the forecast is inaccurate. Excess production not only results in unsold goods but also in increased operational costs and resource waste. For instance, McDonald's might end up with more prepared food than needed, leading to discarded items and unnecessary expenses.

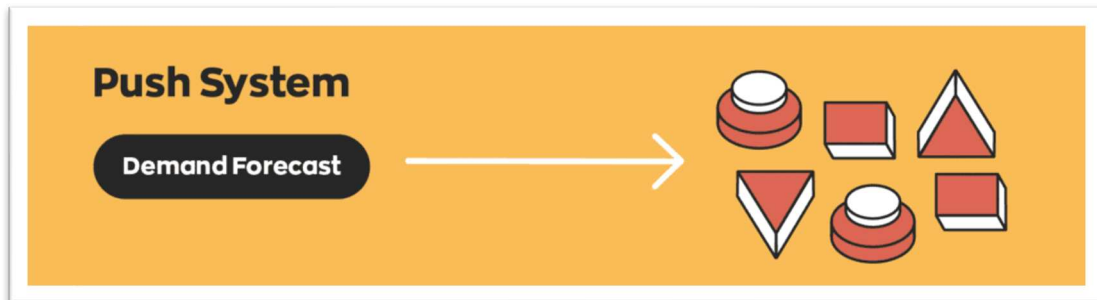


Fig. 3-2 Push system

Push is based on:

- **Forecasting:** Predicting future demand using past data and market trends.
- **Production Planning:** Scheduling production based on the forecasts to ensure efficient use of resources.
- **Inventory Management:** Keeping track of stock levels to balance storage costs with the need to meet customer demand quickly.

To implement this strategy, the push approach relies on software that simplifies prediction and production planning phases. These tools help reduce waste and make production more efficient by analyzing past demand or other techniques and making forecasts more accurate. In the following chapter, we will highlight a software solution.

3.2.1 MRP (Material Resource Planning)

Material resource planning is the most widespread planning method in the world (Miclo, et al., 2015). As mentioned before, it is based on demand forecasts and plans all the manufacturing activities: it is a push flow method. MRP, is a method for effectively planning all resources within a manufacturing company. It encompasses operational planning in units, financial planning in euros, and includes simulation capabilities. MRP is composed of various interconnected processes: business planning, production planning (including sales and operations planning), master production scheduling, Material Requirements Planning (MRP), capacity requirements planning, and execution support systems for both capacity and material. (Miclo, et al., 2015)

To function effectively, MRP (Material Requirements Planning) requires specific inputs to generate outputs that align with the company's capabilities. These inputs include:

- **Bill of Materials (BOM):** A detailed list of raw materials, sub-assemblies, intermediate assemblies, sub-components, parts, and the quantities of each needed to manufacture a finished product.
- **Items Database:** Information on all items, including descriptions, part numbers, and other relevant details.
- **Stockpiles:** Current inventory levels of all materials and components.
- **On-going Orders:** Information on orders that are currently being processed.

By analyzing this information, MRP, coupled with interconnected processes like business planning and production planning, can produce recommended production schedules and purchasing schedules. This ensures that the right materials are available at the right time, minimizing waste and optimizing production efficiency.

3.3 Pull

Opposite from push, pull production “pull” the production from downstream, so from the last component of the process, the final customer. This method ensures that products are only made when there is an actual need for them, minimizing waste and reducing excess inventory.

A familiar example of pull production can also be seen at McDonald's, but in a different context. Outside of peak hours, McDonald's might use a pull strategy where they prepare items only when orders are placed. This way, they avoid preparing food in advance and instead cook items fresh for real-time demand. This ensures that they only use the resources needed for actual customer orders, reducing waste and ensuring fresher products for customers.

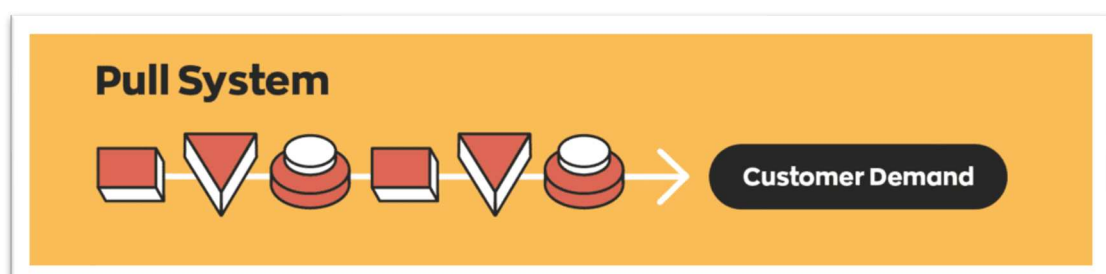


Fig. 3-3 Pull system

The main advantages of pull production include its efficiency in minimizing waste and reducing the risk of overproduction. This approach is highly flexible, as it allows the customization of each product based on customer requests. Since production is based on actual demand, companies can avoid the costs associated with holding excess inventory. However, this approach requires highly efficient communication and coordination throughout the supply chain to ensure timely production and delivery of products. Any delays or disruptions can lead to shortages and impact customer satisfaction. (auxiell, 2023)

Some concepts about pull are:

- **Just-In-Time (JIT):** This principle means producing only what is needed, when it is needed, and in the amount needed. It aims to reduce inventory costs and increase efficiency by responding directly to customer demand.
- **Kanban System:** Kanban is a scheduling system that controls the logistical chain from a production point of view and is an integral part of JIT. It uses visual signals, such as cards or bins, to trigger the production and movement of items through the supply chain.
- **Takt Time:** Takt time is the rate at which products must be produced to meet customer demand. It is calculated by dividing the available production time by the customer demand. This ensures that production is aligned with the pace of customer orders⁴

In conclusion, pull production is a highly responsive approach that aligns production closely with customer demand. By producing only what is needed, when it is needed, pull systems minimize waste and reduce costs associated with excess inventory. However, this approach requires effective communication and coordination within the supply chain to be successful. (auxiell, 2023)

3.4 Push VS Pull

The differences between push and pull production are evident, with each approach offering unique advantages and challenges. Selecting the right system can significantly impact a company's operational performance. The following tables highlight some of the most relevant pros and cons:

⁴ Kanban system and takt time are deepened in the following paragraphs

Table 3-1 Push production advantages and disadvantages (auxiell, 2023)

PUSH
<i>Advantage</i>
Efficiency in high-demand periods: by preparing products in advance, companies can quickly serve a large number of customers
Consistent workflow: production schedules can be planned and managed more easily
<i>Disadvantage</i>
Risk of overproduction: inaccurate forecasts can lead to excess inventory and waste
Higher inventory costs: maintaining large stockpiles increases storage and handling costs

Table 3-2 Pull production advantages and disadvantages (auxiell, 2023)

PULL
<i>Advantage</i>
Minimized waste: by producing only what is needed, pull production reduces the risk of overproduction and excess inventory
Fresher products: customers receive products that are made to order, enhancing quality and satisfaction
<i>Disadvantage</i>
Potential delays: if not managed efficiently, waiting for customer orders can lead to longer lead times and potential delays
Requires precise coordination: effective pull production requires real-time communication and coordination across the supply chain

Both push and pull production systems have their place in manufacturing and service industries. Understanding the strengths and limitations of each system allows companies to choose the most suitable approach for their specific needs or even combine elements of both to optimize their operations. In the following sections, we will analyze situations where one method may be preferable over the other or mixing the method could be the right choice.

3.4.1 Decoupling point – Inventory strategies

Mixing push and pull strategies is not a sacrilege but a smart and winning choice. Most companies must rely on this mix to remain competitive in the market. For example, consider a manufacturer of personal computers in the tech industry. This manufacturer might keep essential parts like motherboards, graphic cards, processors, monitors, and keyboards in stock, relying on various suppliers for these components. When orders for new PCs arrive, the company can quickly assemble and customize the computers using these parts. While the process is driven by customer demand, the components sit on shelves until needed.

In this scenario, the company balances customization and standardization by allowing customers to change certain components like motherboards or graphic cards, but not the external design. This approach enables the company to standardize and produce the external casing in advance using a push production method, while the rest of the process operates on a pull basis. This model is known as Assembly to Order (ATO).

This example illustrates how companies can effectively combine push and pull strategies. Many different organizational models exist in the market, each with its pros and cons depending on the specific process. The image below shows various organizational models: (auxiell, 2023)

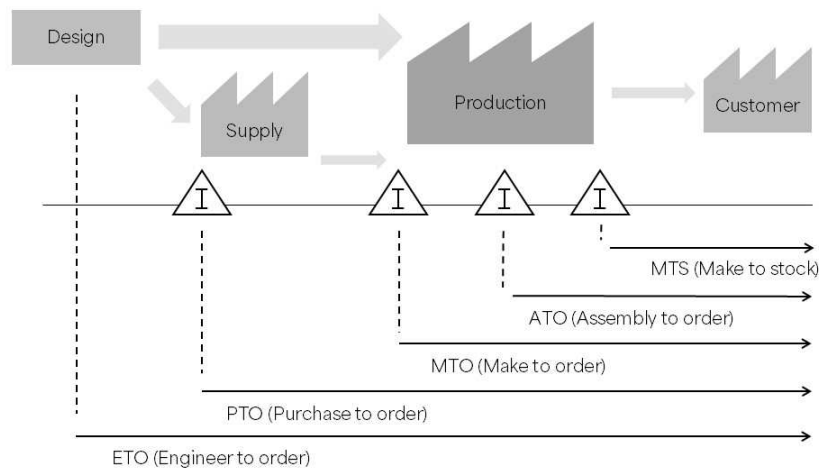


Fig. 3-4 Organizational models (auxiell, 2023)

Make to Stock (MTS) model is based on forecasted demand and products are manufactured in advance and stored as inventory. This approach relies on statistical analysis to predict customer demand, but it does not guarantee that the produced items will be absorbed by the market due to its inherent uncertainty and variability. The key characteristic of MTS is that production is driven

by anticipated demand rather than actual orders so is commonly used in industries where products have a predictable demand pattern, allowing for efficient batch production and inventory management.

Assembly to order (ATO) model as previously mentioned, customization begins at the final stage of the supply chain, specifically during the assembly phase. The ATO system follows a logic similar to mass production for the creation of all its components, which are then produced and distributed in the market. However, the final step before the sale of the finished product introduces a discontinuity in the production system. At this stage, the components are assembled according to the final customer's specific requests, giving the customer an active and decisive role in defining the characteristics of their product.

Make to Order (MTO) model. Here the customization process begins during the production phase. This system manages production cycles based on known demand in advance. Also known as made to order or mass customization, this model is typical of catalog markets and offers a wide variety of customers the ability to purchase personalized items made to their specifications.

Customers usually can choose from a range of prototypes provided by the manufacturer and select their desired features, such as color, design, shape, size, and the addition of elements like text and drawings.

Purchase to order (PTO) model, product customization is done uniquely to meet the customer's specific wishes. Unlike catalog-based customization, PTO does not rely on a predefined list of options to integrate into the product. Instead, it fulfills the customer's specific request by purchasing the chosen elements from the relevant supplier. In this process, the customer submits their customization request, and the production system mobilizes to acquire the necessary components and then proceeds with their assembly.

Engineer To Order (ETO) model, here a specific order begins its journey within the company from the design office. According to this approach, the product is created almost entirely from scratch, designed from its initial configuration based on the customer's specific requests, who essentially selects the aesthetic or functional characteristics from the conceptualization stage. Thus, the production of an ETO product or service only begins after receiving the customer's order. As expected, the ETO system is widely used in sectors requiring a high level of customization, often applied to technically sophisticated projects such as the creation of complex structures and the design of large machinery and transportation equipment. ETO also plays a

crucial role in the digital realm, where the development of custom software solutions with specific functionalities is required.

3.5 Lead time

Lead time is the interval of time that passes from the start of a process until its conclusion (Pavanato, 2020). It's fundamental, when designing a process, to understand the lead time requested by the customer. This is the time the customer is willing to wait from the moment they place the order until they receive the product or service. Accurately determining and managing lead time is crucial for meeting customer expectations and ensuring satisfaction. Taiichi Ohno said: *“All we are doing is measuring the time interval between when we receive an order and when we collect the payment for it. Then, we try to reduce this interval by eliminating non-value-added activities?”* (Panizzolo, 2022). Indeed, lead time comprises the processing time: the actual time needed by a single transforming resource to fully process a unit of product without interruptions. Only a portion of the processing time is composed of activities that add value to the process; all other activities are considered muda (waste). This is why Ohno emphasizes reducing lead time by eliminating these non-value-added activities.

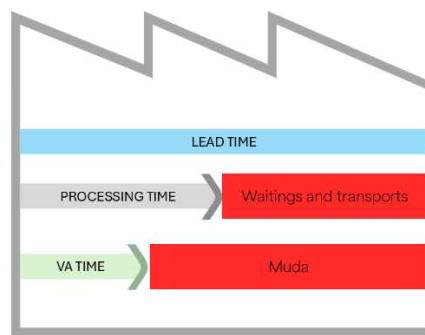


Fig. 3-5 Lead time composition

3.6 Takt time

Takt time is a tool used to set the pace and rhythm of the manufacturing process, aligning it with customer demand. It represents the amount of time allocated to produce each part, such as completing one part every 22 seconds. As a metric, takt time ensures that production meets customer needs without overproduction. As a tool, it helps establish a smooth workflow and eliminate waste in the process. (Womak & Jones, 1996)

$$Takt\ time = \frac{Available\ time}{Market\ demand}$$

Takt time is calculated by dividing the total available production time in a given period by the market demand for that same period. This calculation helps determine the speed at which the production process needs to operate to meet customer demand. For example, if the production line operates for 460 minutes per day and the market demand is 100 pieces per day, the takt time would be 4.6 minutes per piece. This means that the production process has 4.6 minutes to complete one product in order to be align with market demand.

Takt time is a crucial metric in manufacturing because it sets the pace for production to match customer demand. It's the foundation for planning and organizing production processes across different models. Essentially, takt time tells you how fast your production line needs to work to meet demand. If your process takes longer than the takt time allows, it's necessary to decouple the process. Without decoupling, the company risks failing to meet demand, which can lead to financial losses and harm its reputation due to late deliveries.

Identifying the critical point in the production process, where the time needed to complete a task might exceed the takt time, is vital. At this point, introducing a supermarket⁵ becomes essential. By carefully sizing and placing these buffers, you ensure that the production after this point is driven by actual customer orders, rather than by forecasts, which helps prevent delays and improves overall efficiency.

3.7 Cycle time

The second metric is the cycle time, that is the pace of the production. It's the average time elapsed between two consecutive parts exits from the process. Every process has at some point a bottleneck which is the slowest phase of the process that constrains the flow and thus defines the cycle time. If both these metrics are the same, it means that the pace of production is perfectly synchronized with the market needs. Unfortunately, it is very difficult for this to happen. When the cycle time is higher it means that the production is too slow compared to the market demand, on the contrary, if the takt time is higher, overproduction will occur.

⁵ It is a lean tool that decouples two phases of a pull process by inserting a scientifically sized buffer stock, which ensures that the downstream operational flow of the supermarket is not interrupted. This argument is explained more in deep in the chapter 4.4

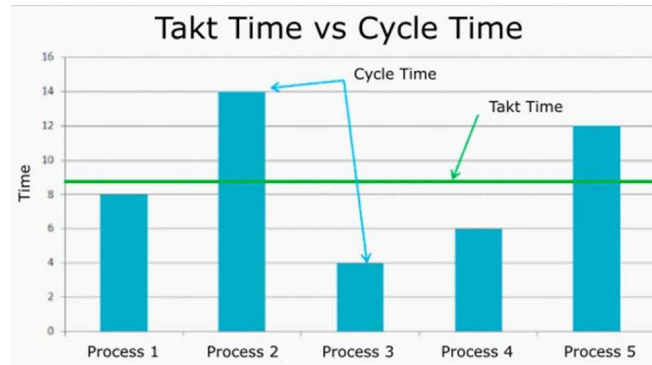


Fig. 3-6 Takt time and cycle time

Here's an explanation on how takt time and cycle time work. The former is represented by a green line, and it represents the time interval that your production process should follow in order to meet customer demand. Essentially, it's the maximum amount of time allowed to produce one unit of product to keep up with customer orders. The latter indicates the actual time taken to complete each process in the production line. In the example shown, Process 2 and Process 5 are identified as bottlenecks because their cycle times exceed the takt time. This means they are slower than the pace required to meet customer demand, which can negatively impact the entire production flow.

To overcome these inefficiencies, a strategic solution could be to implement supermarkets between these processes. These supermarkets can help decouple the processes, ensuring that downstream processes continue to operate smoothly even if the upstream processes are slower. This approach can reduce efficiency losses and prevent economic losses due to delays.

3.8 One-piece-flow

What happens when cycle time and takt time are synchronized? In this scenario, our process capacity is perfectly aligned with market demand allowing a production based on “one-piece-flow”. It is a lean production method where a single unit of product moves through each step of the production process continuously, without waiting in a queue or batch. This approach minimizes work-in-progress (WIP) inventory, reduces lead times, and enhances quality by enabling immediate identification and correction of defects. One-Piece Flow is fundamental to achieving Just-In-Time (JIT) production, as it aligns production rates (cycle time) with customer demand (takt time) and promotes efficiency across the production line. (Liker, 2004)

These are the fundamental rules that govern a correct adoption of one-piece-flow logic: (Sekine, 1992)

1. Synchronize cycle time and takt time: the goal is to coordinate the timing of production with customer needs. In other words, we base the number of items to be produced on the number required by the customers.
2. Base equipment capacity utilization on cycle time: when using large equipment and other devices designed for flexible manufacturing system the complexity increases in terms of coordination with one-piece production.
3. Center production on assembly processes: following a pull production logic is important, information should be shared directly to the assembly department. Information is not passed to any upstream processes.
4. Factory layout must be one-piece-flow friendly:
 - a. Make the factory layout conducive to the overall production flow
 - b. The factory must include clear pathways
 - c. The production line should clearly distinguish between material input and production output
 - d. The production line should consist mainly of single-operator U-shaped cells.
 - e. Include thorough inspection in the layout
 - f. Minimize in-process inventory
5. Goods must be conducive to one-piece production: when dealing with small workpieces is not easy to conduct the production toward one-piece production due to the waste involved in setup time, positioning, and removal of such small items.

Let's consider an example that contrasts batch production with one-piece flow. When the culture of standards is not strong within a company, operators often default to batch production, accumulating goods between operations and creating mini-buffers. Using some numbers:

1. Picking time=3s
2. Assembly time pt.1=4s
3. Weld the cup=9s
4. Assembly time pt.2=6s
5. Final test=20s

The operator begins by assembling part 1 on as many pieces as the available space allows, say 5 pieces. After completing this step, they proceed to weld all the pieces and then place them back in the designated space. Next, they move on to assembling part 2. At this point, the operator

places the pieces into the testing machine. While the machine is working, the operator starts packing the pieces. Once this is done, the cycle repeats.

By working in this way, the operator feels they are optimizing time, as the testing machine, which has the longest cycle time, is constantly running without any downtime. However, this approach leads to several inefficiencies.

Working with intermediate buffers creates a “wave effect” in production. Just like a wave, the pieces move out of the final production phase but then stop when the operator restarts the cycle described earlier. With each new wave, the pieces resume moving out of the production line.



Fig. 3-7 Wave effect

In the example, the operator manages to produce 10 pieces in 310 seconds. The yellow boxes indicate the time required to test each piece. As mentioned, the operator tests 5 pieces consecutively. After that, they prepare the next 5 pieces (with a cycle time of 22 seconds, indicated by the gray boxes), and then test them. The cycle time of the assembly line will therefore be 31 seconds (310/10). The operator thinks they are saving time, but they are actually losing it.

The problem often arises during the bidding phase, where the cycle time is calculated only by considering the bottleneck. What happens every time is that the manual execution times are underestimated. As a result, no one considers the time needed for stages 1, 2, and 4. They underestimate these times and take the 20 seconds of the automatic machine as the production cycle time. Once in production, due to the "wave effect," the cycle time increases to 31 seconds. This leads to an efficiency of only 65% compared to what was projected during the bidding phase.

Introducing a system based on One Piece Flow will allow you to increase both productivity and quality levels.



Fig. 3-8 One-piece-flow or "waterfall effect"

In this setup, the flow is continuous and uninterrupted, like a waterfall. Now, parts will consistently be produced every 22 seconds. Additionally, the operator will process only one piece at a time, which nearly eliminates the chance of errors.

This example clearly illustrates the potential of the one-piece flow method. By synchronizing takt time and cycle time, and eliminating inefficiencies like the wave effect, you can significantly improve both the quality and the productivity of your production line. Adopting one-piece flow doesn't just streamline operations it directly impacts the bottom line, resulting in higher profits and better-quality products.

3.9 Kanban system

This tool is probably the most important part of the system. It works as a visual signal that tells the earlier stage to start the production process. Essentially, it controls the Toyota Production System (TPS) by making sure each production phase begins when needed. We'll take a closer look at this tool and its role in TPS in the next chapter.

4 Kanban system

This chapter aims to describe in detail one of the most effective and widely used tools of the lean philosophy to implement pull-type control: the kanban system. Initially, I will explain what kanban is and outline the different types. Subsequently, I will introduce inventory management and costs, leading to a discussion on the supermarket model. Finally, I will present the formulas for designing a Kanban system and explain the ABC-RRS matrix. This tool forms the basis of my master's thesis, as my project focuses on revisiting and enhancing the potential effectiveness of the traditional kanban system.

4.1 Definition

The kanban system is defined as “the nervous system of lean production because it manages the production just as our brains and nerves manage our bodies” (Productivity Press Development Team, 2002).

In Japanese, the word “Kanban” means “card” or “sign” and is the name given to the inventory control card used in a pull system. A fundamental tool used in the TPS (Toyota production system), the main objective is to control and manage, from a just-in-time perspective, the delivery of material to each workstation and the transfer to the previous stage of the correct information to understand what is needed to produce and in what quantity, thus emphasizing the idea of producing certain goods only when they are needed by reducing overproduction.



Replenishment Kanban			
Part number 4711 2345 2345		Part T800 Central Processor	
Supplier Sirius Cybernetics		Customer Cyberdyne Systems	
Quantity 20	pcs	Packaging EUR Pallet Cage	
			
Location Storage L227 Secure Vault		Kanban Number 1	Kanban quantity 6
			4711 2345 2345

Fig. 4-1 Example of a production kanban card - Kanban card design | AllAboutLean.com

The Kanban system was developed in the late 1940s by Taiichi Ohno to enhance manufacturing efficiency. The concept was inspired by a trip to the USA, where Ohno observed the operation of supermarkets. He was particularly impressed by the replenishment logic used to restock shelves, ensuring a consistent display of products and providing a visual indication of items that needed

replenishment. Consequently, when a customer took a product, it was promptly replaced to align inventory levels with actual consumption. Mr. Ohno tried to replicate this mechanism at the Toyota production plant in Japan (Esparrago, 1988). This observation led Toyota to conceptualize each process as a customer of one or more preceding processes, with those preceding processes functioning as a sort of store producing only what is ordered, when is ordered and in the quantities ordered.

Typically constructed from durable plastic to withstand dirt and dust, Kanbans are actual tags containing essential information for operators. Each kanban is associated with a specific box that contains a specific quantity. Boxes must be standardized because knowing exactly the quantity contained in each box allows for keeping track and calculating the right number of stocks circulating in the factory in that moment. Beyond this useful potential, kanbans bring multiple benefits to the company (Productivity Press Development Team, 2002).

- Eliminating overproduction, the number one of wastes
- Increase flexibility to respond to customer demand
- Coordinate production of small lots and wide product variety
- Have a simplified procurement process
- Integrate all processes and tie them to the customer
- Find simple, visual, replenishment information, production instructions and reduce the usage of MRP
- Eliminate unnecessary WIP inventory
- Uncover hidden waste
- Autonomous maintenance

The table below compares the major differences between a system managed by MRP and a kanban system.

Table 4-1 Comparison between MRP and Kanban system (auxiell, 2023)

MRP	KANBAN
Spot agreements on lead time and supply conditions	Medium-term agreements on Lead Time and supply conditions
Supplies based on consumption expected even in the short term	Reintegration of consumed materials, in independent of consumption short-term forecasts
Need to consider the LTs of the suppliers for the scheduling of production	Production scheduling may not consider the LTs of the codes managed at kanban, since this provides for

	the automatic replenishment of what is consumed
No visual control within the enterprise	Visual control within the enterprise
Absence of continuous sharing of information between customer and supplier	Full synchronization of information between customer and supplier
It is possible to check the availability only close to the production date	Continuous and advance check on the Punctuality of supplier delivery

All these improvements are verified and work as long as six fundamental rules are respected (Japan Management Association, 1985).

Rule 1 – Do not send defective products to the subsequent process: this is the worst waste of all, because it directly affects cost reduction, which is the goal of any industry. To overcome to this problem, machines must be made to stop automatically when they produce defectives, and workers must stop their operations. *Jidoka* is a system that enables the machine or operators to be automatically detected when an abnormal situation occurs and to detect the fault then stop the production. (Durakbasa & Gencyilmaz, 2018)

Rule 2 – The subsequent process comes to withdraw only what is needed: a loss is created if the preceding process supplies parts and materials to subsequent process at the time it does not need them or in a quantity above the latter's needs. The loss can be generated by different circumstances, including a loss from excessive overtime, an excess of inventory or investing in new facilities without knowing that the existing facility is enough.

Rule 3 – Produce only the exact quantity withdrawn by the subsequent process: this rule is a logical consequence of the previous one. It is predicated on the condition that the process itself must restrict its inventory to the absolute minimum. For this reason, these conditions must be respected:

- a) Do not produce more than the quantity required by the kanban
- b) Produce in the sequence in which kanbans are received

Rule 4 – *Heijunka*⁶: in order to respect the third rule, processes must be synchronized to maintain machines and workers in such a way that materials can be produced at the time needed and in the quantity needed.

Rule 5 – *Kanban is a mean to fine tuning*: for the workers, the kanban become a source of information for production and transformation. They must rely intensively on the kanban to do their work, the load-smoothing system of production becomes extremely important.

Rule 6 – *Stabilize and rationalize the process*: this is a fundamental condition for the proper functioning of other rules. Efforts toward standardization and process rationalization are essential for the successful implementation of automation.

4.2 Types of Kanban

Kanban is so versatile it can be used throughout the whole system; from the purchasing department to the production department. Different situations required different information, but ideally, they should be as thorough as possible and include the following kind of information:

- The material, part, subassembly number
- A description with a photo or drawing
- The previous process
- The next process
- The internal or external supplying process
- The customer order number
- What, when and how much to withdraw
- What, when and how much to make

Yasuhiro Monden, in his book, mentioned three main types of kanban characterized by their aim and the place for which that tag was designed (Monden, 2012).

⁶ *Heijunka* is a lean manufacturing tool that aims to distribute labor-intensive tasks evenly throughout the production schedule. This approach allows for higher average utilization while maintaining a constant cycle time (İşler & Güner , 2014)

4.2.1 Purchasing kanban

The purchasing Kanban is specifically designed to manage the replenishment of materials or components from external suppliers. It acts as a signal to trigger new orders when stock levels fall below a predetermined point. The purchasing Kanban contains critical information such as the item code, supplier details, and required quantities. By aligning procurement activities with actual consumption, the purchasing Kanban ensures that materials are ordered just in time, reducing excess inventory and avoiding stockouts.

4.2.2 Production kanban

This is the type of Kanban most people refer to; it is used in various sectors, from manufacturing to software development. A production-ordering Kanban closely resembles the standard production order used in a push system. It specifies what needs to be produced and in what quantity. When a withdrawal Kanban authorizes the removal of parts from a line or cell, production-ordering Kanbans initiate production to replace the parts that have been removed.

4.2.3 Transport Kanbans

The transport Kanban indicates when numerous parts need to be moved to the production line or between processes in production and assembly. The information provided by this type of Kanban includes the item code, destination and origin of the parts, type of transport, number of items...

4.3 Kanban management methods:

Specifically, four management methods with kanban are described below.

The "Pure" Kanban, which could be of two kinds:

- A single card: it uses only production or transportation kanbans and the supermarket⁷ is located right next to the place of usage.
- A double card: it requires both production/transportation kanbans and withdrawal kanbans. This applies to multi-plant companies due to the fact that more product codes are managed and it is impossible to place the supermarket in the line. In this case, we need two supermarkets, the main one and the localized one.

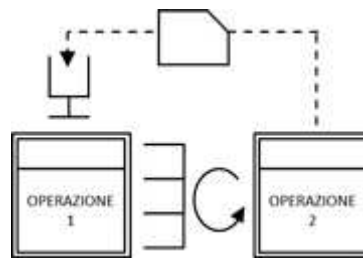


Fig. 4-2 Scheme of a pure kanban

The batch kanban:

- The batch kanban is powerful when the reorder quantity is different from the quantity required by the kanban. For example, when the economic lot of the supplier is too large compared to the expected requirement in the restoration lead time. However, this system is quite complex because the release of a kanban is not directly connected to an order generation. Indeed, this method is usually supported by a software.

The signal kanban:

- Signal Kanban is implemented in production systems when the supplier's production batch is large compared to the customer's consumption. Signal kanban visually and physically repurposes the supply policy with reorder points. The kanban is no longer associated with a container but is sent to the supplier only after a certain number of containers or pieces have been consumed.

⁷ A "supermarket" is a lean tool that decouples two stages of a pull process, through the inclusion of a scientifically sized stockpile that allows the operational flow downstream of the supermarket not to be interrupted (auxiell, 2023)

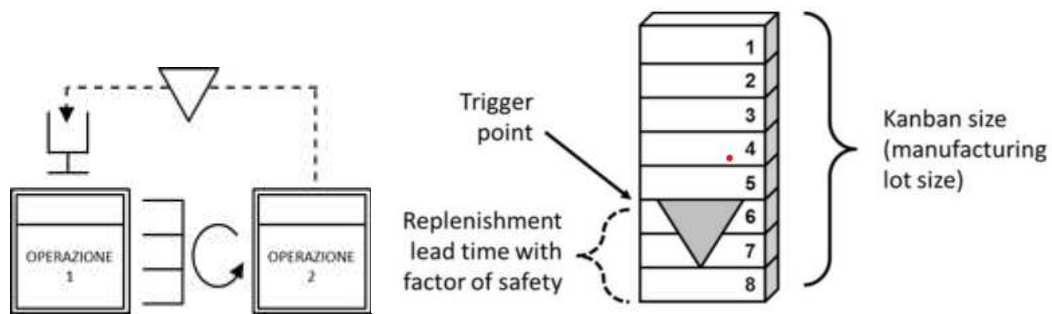


Fig. 4-3 Scheme and reorder point of a signal Kanban

The double bin:

- The double bin is the simplest method of kanban implementation. It consists of using only two kanbans and the empty-to-full logic where the empty bin represents the restoration order. This method is useful for cheap and high-volume items such as screws or fasteners.

4.4 Rules for dimensioning the kanban

Physically, Kanban is just a tag placed outside of a box. To exploit its true potential, dimensioning to find out the right number of cards needed in the process is necessary. The number of kanban cards in circulation represents the amount of stock in the warehouse. This stock is directly linked to the economic value of the inventory. By accurately calculating the number of cards, companies can better control inventory levels, ensuring they keep enough stock to meet demand without overproducing or holding excess.

Below is represented a methodology for dimensioning kanban system (Pavanato, 2020)

$$\#KB = \left\lceil \frac{C * (LT + LT_s)}{Q} \right\rceil + 1$$

Where:

- LT = replenishment lead time [days or hours]
- LT_s = safety lead time [days or hours]
- Q = quantity of items that fit in a box [pcs]
- C = maximum consumption during the lead time [pcs/units]

The value “+1” represents an extra container to be added to the sizing according to the fact that the first kanban will be detached when the first container is emptied.

The maximum consumption during the lead time, C , is calculated using the moving average, with the lead time itself serving as the averaging period.

The previous formula expresses the maximum number of bins that will need to be in stock; however, this stock, under normal conditions, will only be present when the system is initially started. Therefore, the maximum stock in a supermarket is the sum of the quantity of the individual Kanban.

$$\text{Average inventory level} = SL + SS$$

Where:

$$SL = \text{stock for batch restoration} \rightarrow SL = Q/2$$

$$SS = \text{safety stock}$$

Safety stock is additional stock to protect against uncertainties in demand, variations in lead times, changes that occur in supply and quality problems. It is calculated by subtracting from the actual trend with safety stock (number of kanban = $\#KB$) the ideal trend without safety stock ($\#KB'$). Below is the formula for calculating the latter.

$$\#KB' = \frac{C_{avg} * LT_R}{Q} + 1$$

Where:

$$C_{avg} = \text{average consumption}$$

$$LT_R = \text{real lead time}$$

The formula to compute the safety stocks is the next one:

$$SS = (\#KB - \#KB') * Q$$

Therefore, using the previous formula to calculate the average inventory level we obtain:

$$\text{Average inventory level} = \left(\left[\frac{C_{max} * (LT + LT_s)}{Q} \right] - \frac{C_{avg} * LT_R}{Q} \right) * Q + \frac{Q}{2}$$

The result of these formulas is related to customer demand at that time; this means that any fluctuations in demand correspond to variations in the number of kanban tags. The number of kanban is in fact a dynamic value that can vary. The formulas just seen make it possible to

determine the minimum number of kanbans needed to handle a certain component, up to a steady state condition in which stocks of the component. (Pavanato, 2020)

4.5 Supermarket

We often define the aim of lean thinking as the “full satisfaction of client needs by continuously producing and delivering what the client wants”. This idea naturally leads us to embrace the concept of flow, and to reduce or altogether eliminate everything that interrupts that flow.

However, achieving a smooth flow of products or services to customers, tailored to their needs, is often more difficult than it seems. Various factors can interfere with this process, such as waste, a lack of exclusivity (where one client’s production prevents production for another), uneven production speeds across different stages (due to differences in cycle times or batch sizes), and differences in working shifts between clients and suppliers. These issues typically interrupt the flow, leading to longer lead times and higher levels of work-in-process (WIP). To address these interruptions, lean organizations often use what is called a "supermarket."

A supermarket is a lean tool that separates two stages of a pull process by keeping a carefully sized stockpile of inventory. This stockpile ensures that the downstream process keeps flowing without interruption. Often managed using kanbans, it helps to keep materials flowing smoothly, with boxes always available for use and ready to be replenished.

Additionally, the supermarket should be placed upstream of the pacemaker process. The pacemaker is the point in the production process where the production lead time matches the amount of time a customer is willing to wait. By placing the supermarket here, production remains stable and can quickly respond to customer demand, while also avoiding delays. This smart placement of the supermarket keeps the production flow smooth, balancing supply with demand and helping to reduce waste or downtime in the production process. (auxiell, 2023)

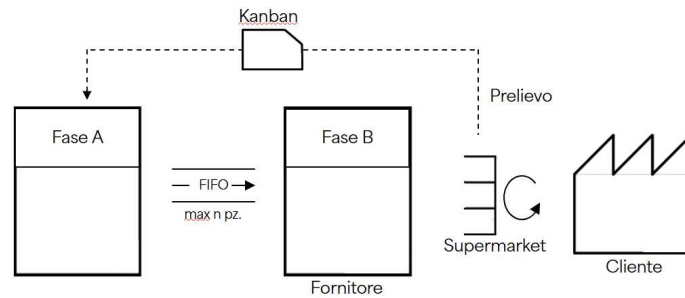


Fig. 4-4 Representation of a supermarket and kanban logic (auxiell, 2023)

Some benefits of the supermarket, according to auxiell (2023) are:

- autonomous withdrawn by the customer
- Stockpile of materials always available
- Visual management
- Using the supply container to eliminate transfers

4.6 Inventory management

The fundamental components of the kanban system include inventories. Below, I will provide an overview of inventory management.

4.6.1 Definition

Inventories are resources of any kind having an economic value. An inventory consists of raw materials, work-in-progress (wip), finished goods, consumables and stores. With the term “management” we intend to plan and devising procedures to maintain an optimal level of these resources (Chandra Bose, 2006).

4.6.2 Inventory management

Traditionally, academic literature on inventory has emphasized production and procurement as the primary factors influencing corporate inventory policy and management. The balance between ordering costs and holding costs defines the transactions approach to inventory management, as exemplified by the EOQ⁸ and (S, s) models developed many decades ago.

⁸ (EOQ) Economic order quantity is the order quantity that minimizes total inventory holding costs and ordering costs. It is the optimal replenishment order size of inventory item that achieves the optimum total inventory cost during the given period of time (Samak-Kulkarni & Rajhans, 2012)

Nowadays, the field of operations management has introduced new concepts in inventory control. These management-oriented topics include Material Requirements Planning (MRP) systems, Just-In-Time (JIT), and Enterprise Resource Planning (ERP) methods. Despite the theoretical and practical limitations of these concepts and techniques, their application in real business situations should positively impact a firm's performance.

Inventories can be categorized based on their functional purpose and provenance (Lombardi, 2008). We have raw materials, semi-finished materials, and final products that are ready to be sold. Stocks are divided into different categories: internal stocks, which come from processes within the organization, and external stocks, which are managed by suppliers. Furthermore, stockpiles are classified based on their function in inventory and the motivations underlying stockpiling decisions: (Krajewski, et al., 2015)

1. **Cycle:** Cycle inventories arise from the need to have a product on hand when it is not possible or convenient to produce or order it. Inventories are accumulated to meet demand for the specific period required to produce or receive the item.
2. **Pipeline:** Also called in-transit stocks, these are sent by a supplier but not yet delivered to the customer. Unlike cycle stocks, they may not be physically present in the warehouse.
3. **Safety:** These are extra inventories maintained to safeguard against unpredictable demand, fluctuations in lead times, supply chain disruptions, and quality issues.
4. **Decoupling:** Within the production process, stocks can be used at key points to make upstream and downstream operations independent of each other.

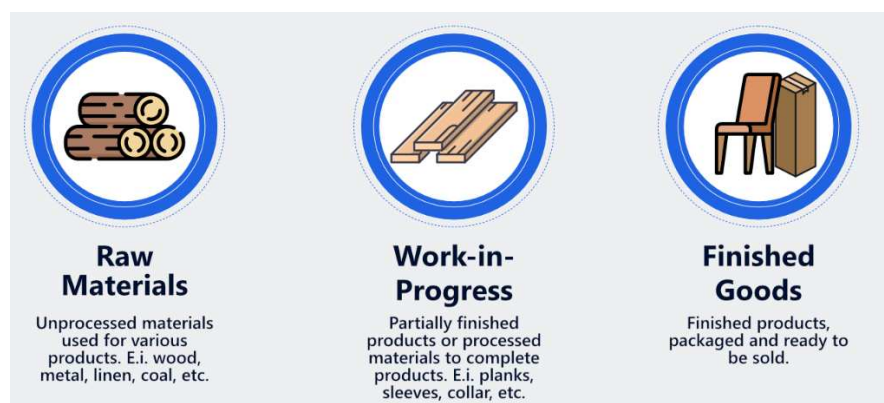


Fig. 4-5 Representation of raw materials, WIP and finished goods

Nearly all the literature on optimal inventory management employs criteria of cost minimization or profit maximization. For example, an inventory manager's goal is modeled as minimizing costs or maximizing profits while meeting customer demands. If inventory decisions do not impact the revenue stream, these two criteria result in the same optimal replenishment policy.

In conclusion, determining the optimal inventory level is a critical issue in operations management, as inventory represents both an asset and a liability. Excess inventory can occupy valuable space, incur financial costs, and risk damage and loss, while also masking inefficiencies in management and processes. Lean production principles, mentioned by Womack and Jones (1996), suggest that reducing inventory levels can mitigate these issues, though demand volatility can pose challenges to this approach. Conversely, insufficient inventory can disrupt manufacturing operations and degrade customer service, potentially leading to lost business if products are not readily available. (Koumanakos, 2007)

4.6.3 The service level

The service level is an important Key Performance Indicator (KPI) that, in simplified terms, measures a company's ability to fulfill customer demand, expressed as a percentage. In inventory management, the service level is defined as the probability that customer demand is met or does not exceed inventory levels (Priniotakis & Argyropoulos, 2018). For example, a service level of 95% means that 95 times out of 100, there is sufficient stock to satisfy customer orders on time, while the probability of stock-outs, resulting in missed sales, is 5%. Since future demand is uncertain and unpredictable, achieving a service level of 100% would require an infinite amount of inventory, which is clearly unattainable. Therefore, management must understand the trade-off between the cost of inventory and the cost of stock-outs and determine inventory levels based on specific criteria.

In the picture below, it is shown that as the service level increases, the average daily consumption value used to calculate the number of Kanban tags also increases.



Fig. 4-6 Variation in the average daily consumption to be considered when calculating the number of kanban based on the safety level chosen

4.6.4 ABC-RRS Matrix

The significance of the ABC analysis is reflected in the fact that it enables the monitoring of inventories as well as the determination of potentially useful inventories and those that do not contribute to the goals but rather are costs and are a burden for the enterprise. In other words, its aim is to determine the right management method for each component. The ABC classification enables inventories management at several levels, in compliance with their importance.

Inventories are categorized into groups according to the Pareto principle, which states that, for many events, roughly 80% of the effects come from 20% of the causes. In a case of a business, it could be stated that roughly the 20% of the end products generates the 80% of the income. In ABC analysis, a company reviews its inventory and sorts all items into three categories, called "A" items, "B" items and "C" items. (Priniotakis & Argyropoulos, 2018)

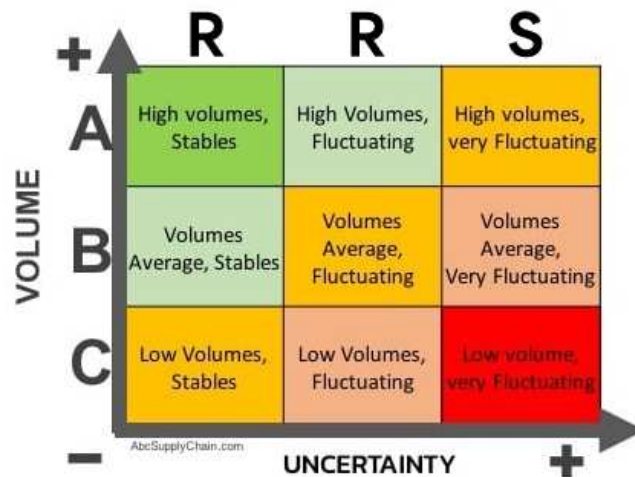


Fig. 4-7 A generic ABC-RRS matrix

A typical breakdown would possibly describe “A” items as those that produce 70% of income, “B” items as those that produce 25% of income and “C” items, as those that produce 5% of income. This classification might be different from company to company, but managers should be able to find the pattern that suits best their needs. Clearly, “A” items require closer attention and should be handled differently. Assigning higher Service Levels for those items is a wise choice. The higher service level will lead to higher inventory but will also decrease the probability of a stock out. A 5% probability of a stock out for an “A” item will result to much higher losses than of a 5% probability for a “C” item. A 99% Service Level for an “A” item could have about the same impact as an 85% Service Level for a “C” item and managers should position against each category accordingly. (Priniotakis & Argyropoulos, 2018)

Meanwhile, the Runner, Repeater, Stranger (RRS) classification system provides additional insight into inventory management by categorizing items based on their frequency of use. This classification complements ABC analysis, offering a more nuanced understanding of inventory dynamics. By cross-referencing ABC and RRS classifications, companies gain a comprehensive overview of their inventory landscape. For example, 'A' items identified through ABC analysis may include both 'Runners' and 'Repeaters,' indicating high-value items that contribute significantly to revenue generation and are frequently used. This dual classification approach enables managers to tailor inventory management strategies based on the unique characteristics of each category, optimizing resource allocation and customer service priorities.

4.7 Inventory cost

One crucial aspect that is often overlooked in inventory management is the delicate balance required between maintaining higher and lower stockpiles. The primary goal for an inventory manager is to find an optimal trade-off between these two extremes. On one hand, excessive stockpiles tie up capital and resources that could otherwise be utilized more effectively within the company. On the other hand, insufficient stockpiles risk disrupting operations and customer satisfaction. Therefore, it is essential to recognize that stockpiles, while necessary to a certain extent, represent a use of capital that does not directly contribute to the company's profitability and incurs additional costs for maintenance and storage.

In the following sections, we will explore the reasons for maintaining higher inventory levels, as well as the arguments for keeping inventory levels low, highlighting the advantages and disadvantages of each approach.

4.7.1 Reasons for keeping the stockpile level low

As previously said, maintaining excessive stockpiles leads to increased maintenance and storage costs while tying up capital that could be better utilized elsewhere, ultimately not contributing to the company's profitability. Indeed, inventories are affected by different costs, here are the three main categories are described according to (Krajewski, et al., 2015):

1. **Holding cost:** related to taxes, insurance and physical decline of goods:
 - a. Cost related to warehouse management and tools. This includes rental costs, electricity, heating, equipment depreciation, and insurance expenses.
 - b. Manpower costs.
 - c. Fiscal costs. Variations in stockpile amounts affect the income statement by impacting the pre-tax results.
 - d. Cost of obsolescence. Items stored in the warehouse may undergo technological obsolescence or physical deterioration, leading to a decrease in their economic value over time.
 - e. Depreciation of raw materials. If the market price of commodities has decreased since their purchase, the company will incur such a cost.
2. **Capital cost**

Refers the opportunity cost of investing in an asset relative to the expected return on assets that carry similar risk.

3. Carrying costs

Also known as “holding costs,” refer to fees associated with maintaining inventory in stock. Carrying costs vary significantly depending on the type of product being sold and managed. Particularly, products with a limited shelf-life or requiring consistent handling, movement, and restocking tend to incur higher expenses.

4.7.2 Reasons for keeping stockpile level high

After examining the costs associated with maintaining goods, one might wonder why not eliminate them altogether? Here are some reasons why stockpiles are fundamental:

1. **Service level:** Inventories are accumulated to quickly meet customer demand and improve company punctuality. Higher stocks reduce the probability of stockouts and backorders. Stockouts represent the inability to satisfy the client, resulting in lost sales, while backorders indicate delays in order delivery.
2. **Ordering cost:** the generation of an order incurs a cost. For the same item, the ordering cost remains constant regardless of the volume ordered. Placing an order is also time-consuming for the operator. The quantity ordered is often tied to potential discounts, so striking the right balance between price and quantity is crucial.
3. **Set-up cost:** this is associated with the cost of reconfiguring the machine for the next operation. Set-up costs are independent of the order quantity. Therefore, having a large quantity of items stored in the warehouse may encourage ordering more pieces to optimize set-up costs, rather than considering smaller and faster batches.
4. **Transportation cost:** Larger orders can better amortize transportation costs. Consequently, the pressure to order more items than needed to amortize the cost often leads to unnecessary orders.

This graph effectively illustrates the trade-off between holding costs and ordering costs in inventory management. As the reorder quantity increases, holding costs also rise, contributing to an increase in total costs, while ordering costs decrease. Therefore, companies must strike a balance between these opposing trends and select the appropriate economic order quantity

(EOQ). By analyzing this trade-off, companies can make informed decisions to optimize their inventory processes, reduce costs, and enhance operational efficiency.

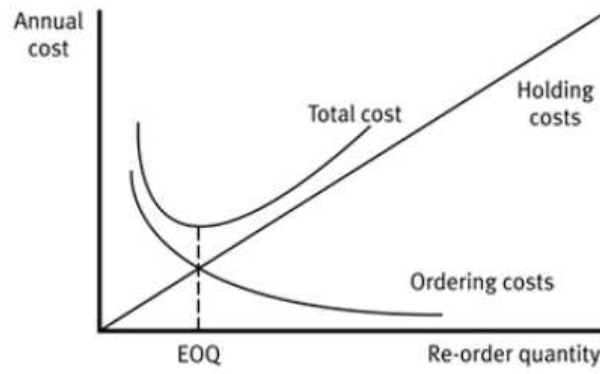


Fig. 4-8 Trends of stockpile cost and EOQ representation (Koumanakos, 2007)

5 The new kanban formula

All the theoretical concepts discussed earlier were meant to enhance your understanding of pull system sizing. In this chapter, I'll delve into my master's degree project, outlining the key aspects of my research.

The journey begins with an analysis of various market demand scenarios, followed by a closer look at the specific characteristics of market demand. I'll then explore the new parameters influencing the new kanban formula and the research I conducted during my internship in auxiell Spa. This involved creating a dataset using Python⁹ to automate the calculation of new parameters and varying numerous factors to enhance the accuracy of the analysis. Finally, I'll compare the benefits of my study with the traditional Kanban sizing formula, highlighting the improvements achieved and the possibilities to fine-tuning the formula for each specific scenario.

5.1 Case study

During my internship, I had the chance to work on a project focused on pull system sizing in a company we will call Acme Spa for privacy reasons, which manufactures water metering systems. My role was to analyze and help implement a kanban system to better manage the flow of components between the supply side and the warehouse. Auxiell Spa supported Acme Spa, which had been facing challenges in managing the production of a specific water metering system model.

The project was divided into two main phases: manufacturing and supply. For the purposes of this thesis, we will focus on the supply side, where we introduced a kanban system for key components. The warehouse played a critical role in this process. As with many companies, Acme Spa's warehouse needed to align its stock management more closely with production demands. This meant organizing stock in a way that allowed for quick and accurate picking whenever and wherever required. Given its role in the supply chain, the warehouse ensures the availability of components when production needs them, reducing delays and improving overall workflow.

⁹ Python is a versatile programming language known for its readability and simplicity, widely used in web development, data science, machine learning, and automation, supported by a rich ecosystem of libraries and frameworks

One of the challenges we faced was the lack of standardization and communication between the warehouse and production teams. Their priorities were often not aligned, and for some items, stock levels were far too high, tying up warehouse space unnecessarily and creating high carrying costs. To solve this, we worked on setting up a kanban system that focused specifically on the components required for a certain production line.

The first step of our analysis was to understand the products in detail: the bill of material¹⁰, which components were prevalent in the production cycle, and the various steps involved in production. With this information, we developed an ABC-RRS matrix to analyze component consumption over the year 2024. The matrix helped us classify components based on their value and usage frequency into categories: A-Runner, B-Runner, A-Repeater, and B-Repeater. Runners represent high-frequency items, while Repeaters are used less often but still frequently enough to be essential. While the category A refers to the economic value; A-items cover the 80% of the total amount, B-items 15%.

Once the matrix was complete, we could see how to implement the kanban system to regulate stock levels more effectively. Kanban cards were used to trigger new orders only when needed, eliminating the overproduction of certain items and ensuring that stock levels remained in line with actual demand. This had the added benefit of freeing up space in the warehouse and lowering the inventory costs.

Kanban's benefits don't stop at improved stock control. The system also makes processes smoother by reducing waste, one of the key principles of lean manufacturing. It helps reduce overproduction, lowers the amount of work-in-progress inventory, and minimizes waiting times by better synchronizing production with actual demand. Moreover, kanban incentives continuous improvement (kaizen) by making inefficiencies easier to spot and correct. It creates a more flexible, responsive system that can quickly adapt to changing market conditions, helping the company remain competitive.

Another important advantage of kanban is its visibility and hands-on nature. Unlike hidden MRP rules, which can be hard for operators to influence, kanban is something that the people working

¹⁰ A Bill of Material (BOM) is a detailed list of all the components, raw materials, assemblies, and sub-assemblies needed to manufacture a product. It includes the quantity of each item, descriptions, and sometimes the sequence in which they are used during production. The BOM serves as a blueprint for building a product and is essential for inventory management, production planning, and cost estimation (APICS Dictionary)

in the process, like warehouse staff, can physically see and interact with. This direct involvement allows them to identify bottlenecks or inefficiencies and contribute to improving the process.

In conclusion, this project highlighted the importance of kanban in making supply chains more efficient and reducing unnecessary costs. By aligning the warehouse and production processes, the system ensured that the right components were available when needed, in the right quantities, and without unnecessary delays. In the long term, this not only reduces waste and increases efficiency, but also improves overall productivity.

5.2 Examining different market demand scenarios

First of all, a critical step in dimensioning a pull system, regardless of the specific objectives, is understanding the different market scenarios. Auxiell, with its diverse client base, deals with companies across various industries: from apparel manufacturers to firms producing mechanical components, electric mowers, and highly sophisticated machinery. With such a variety of clients, it is essential to begin by analyzing external market factors to ensure that the internal analysis is conducted in a way that aligns with these factors.

External analysis involves understanding market dynamics that can be influenced by unpredictable factors, which may necessitate assumptions when evaluating future conditions. It's important to highlight that any forecast contains a degree of uncertainty, and this can be influenced by elements such as data accuracy and the ability to correctly interpret market trends.

For example, factors like seasonality should be carefully considered, especially when studying the products offered by a company and how the market responds to them over time. Misinterpreting such variables can lead to inaccurate demand forecasts, which, in turn, can affect pull system sizing and lead to inefficiencies. Therefore, the process of reading and understanding market trends becomes essential in developing a reliable forecasting method that minimizes the risk of inaccuracies. Kanban systems, when sized correctly, allow for adjustments in inventory based on real-time demand, making them more responsive to changes. However, without accurate data and an understanding of market trends, the sizing of kanban cards may either underestimate or overestimate demand fluctuations.

5.2.1 Characteristics of market demand

Market demand is characterized by a range of interconnected factors, each influencing how companies must adjust their production and inventory strategies to remain efficient.

Understanding these characteristics is essential when designing and sizing a pull system, such as kanban, as they directly impact the fluctuation and predictability of demand. Key factors include (Beggs, 2018):

- Price Sensitivity: The relationship between the price of a product and the demand for it is critical. When prices decrease, demand often rises, and when prices increase, demand can drop. This price elasticity requires companies to closely monitor market prices and be prepared to adjust inventory levels in response to these shifts. In some cases, the effect may be immediate, while in others, it may take time for changes in pricing to affect consumer behavior.
- Consumer Preferences: Shifts in consumer tastes, trends, and preferences can significantly impact demand. As consumer behavior evolves, whether due to changing fashion trends, technological advancements, or cultural influences, companies must adapt their inventory and production systems to align with these new demands.
- Income Levels: The economic environment and changes in income distribution affect consumer purchasing power. In times of economic growth, demand for both essential and luxury items may increase, whereas during economic downturns, consumers may reduce spending, particularly on non-essential goods.
- Substitutes and Complements: The availability of alternative products (substitutes) and related products (complements) can greatly influence demand. For example, if a substitute product becomes cheaper or more popular, demand for the original product may decline. Conversely, an increase in demand for a complementary product may drive up demand for associated goods.
- Seasonality: Many industries experience demand cycles that are closely tied to seasons, holidays, or specific times of the year. Seasonal peaks, such as winter seasons, holiday shopping, or weather-driven product demand, require companies to temporarily adjust their production and inventory strategies to accommodate increased or decreased demand.
- Expectations of Future Prices: Consumers' expectations of future price changes can also influence current demand. For instance, if customers anticipate a price increase, they may accelerate their purchases, leading to a temporary spike in demand. On the contrary, if they expect prices to drop, they may delay purchases, causing demand to slow down.

Understanding these characteristics helps companies align their pull systems with real-world market conditions, enabling them to respond effectively to both predictable patterns and unexpected demand shifts. In kanban sizing, this understanding is especially important because it ensures that inventory levels are well dimensioned, reducing the risk of inefficiencies such as overstocking or stockouts.

The formula for calculating kanban sizes directly derives from the analysis of variables influenced by market demand. Specifically, it focuses on:

- Average demand: This refers to the average quantity of a product consumed or sold over a specified period. It helps in determining how much stock is generally required to meet regular demand levels.
- Standard deviation: This measures the variability or volatility of demand over time. A higher standard deviation indicates greater fluctuation in demand, which requires more inventory to accommodate fluctuations.
- Service level: The service level is the desired probability that stock will be available to meet customer demand without shortages. A higher service level implies more stock to avoid stockouts, but it also increases inventory costs.
- Lead time of supply or replenishment: This is the time it takes to replenish stock after an order is placed. Longer lead times mean that more inventory is needed to cover the gap between placing an order and receiving new stock.
- Frequency of issuing purchase or production orders: This refers to how often orders are placed to replenish inventory or initiate production. More frequent orders can reduce the amount of stock needed but may increase ordering costs.

Kanban's flexibility lies in its ability to adjust inventory levels in response to real-time demand signals, minimizing the risks associated with inaccurate forecasts. This adaptability makes it an ideal tool for managing unpredictable demand with greater precision.

In the context of lean production, a well-structured external analysis helps in aligning production processes more accurately with customer demand, ensuring that a pull system, like kanban, operates at maximum efficiency.

Moreover, the auxiell lean system emphasizes that a solid analysis begins by following the SPDCA cycle. As mentioned earlier, the first “S” stands for “Scan,” referring to scanning the external environment. This step is crucial for building a strong foundation before moving into the planning phase. By doing so, companies can improve data accuracy, reduce the need for future revisions, and consequently save costs by minimizing labor expenses.

5.2.1.1 Average demand & standard deviation

A special focus on average demand and standard deviation is essential. When starting a new analysis for implementing a kanban system in a new company, or when analyzing its backlog to make strategic decisions, understanding these two variables is fundamental. They provide insight into how sales or the supply of certain components are performing, as well as their stability over a given period.

The process begins with the consumption matrix provided by the company, which shows the consumption [pcs] of each item over a specific period¹¹. Below is an example:

codice	202401	202402	202403	202404	202405	202406	202407	202408	202409	202410	202411	202412	202413	202414	202415
1.ETRMD.0063	-	-	-	-	-	20	-	-	-	-	-	-	-	-	-
1.ETRMD.0322	-	40	260	497	20	418	-	39	-	-	15	12	-	-	-
1.ETRMD.0323	-	-	140	101	131	5	159	-	12	-	-	-	-	-	-
1.ETRMD.0324	-	-	13	-	59	-	8	-	39	-	-	-	-	-	-
1.ETRMD.0325	-	-	100	140	47	3	257	-	-	-	12	12	-	-	-
1.ETRMD.0341	-	330	400	100	600	190	1.050	850	520	541	990	593	64	200	-
1.ETRMD.0341ITA	-	-	-	-	50	-	18	68	40	-	50	-	-	50	-
1.ETRMD.0343	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1.ETRMD.0344	-	1.000	-	-	-	-	-	-	-	-	-	-	-	-	-
1.ETRMD.0348	-	1.300	-	900	690	110	-	450	-	-	650	-	50	-	450
1.ETRMD.0349	-	460	350	-	40	90	-	250	150	-	-	-	-	-	130
1.ETRMD.0352	-	1.533	590	150	1.050	100	-	300	1.060	341	300	600	-	-	50
1.ETRMD.0352ITA	-	70	30	80	-	70	100	160	115	310	50	-	-	-	150
1.ETRMD.0358	-	1.920	480	2.640	4.080	1.200	1.680	5.760	9.840	2.160	2	6.480	240	-	2.390
1.ETRMD.0372	-	160	-	160	80	-	40	-	-	20	-	-	19	-	-

Fig. 5-1 Example of consumption matrix

From this input, the calculation of average demand and standard deviation is done to give a first impression of demand patterns. In the traditional kanban formula, it is often preferred to calculate a moving average based on a specific period to level out peaks or valleys in demand. This approach makes the average demand more reliable and less influenced by outlier periods that could distort the results. For example, months like August, when many companies close for holidays, can significantly affect the average if not accounted for properly.

¹¹ The number representing the week is structured by combining the year (2024) with the corresponding week number (01). I chose this format because it ensures that when the data is sorted in Excel, the weeks remain in the correct chronological order.

Meanwhile, “standard deviation is a statistical measure that indicates the degree of variation or dispersion in demand. It shows how much individual data points deviate from the mean (average). A low standard deviation suggests that demand is stable and close to the average, while a high standard deviation indicates significant variability” (Triola, 2018). This measure is crucial for calculating safety stock. As standard deviation increases, the amount of stock needed to cover fluctuations also rises, leading to higher inventory levels in the warehouse to compensate for unpredictable demand changes.

These two variables, average demand and standard deviation, are critical in kanban sizing and can greatly influence the overall system design. Therefore, a clear understanding of these factors is essential for accurately dimensioning the system.

5.2.1.2 *Coefficient of variation*

The coefficient of variation (CV) is a key statistical measure used to assess the relative variability of demand in relation to its average. It is calculated as the ratio of the standard deviation to the average demand, expressed as a percentage.

$$CV [\%] = \frac{dev_{std}}{mean}$$

This measure provides insight into the level of consistency or unpredictability in demand patterns. A low CV indicates stable demand with minimal fluctuations, while a high CV suggests greater variability and potential uncertainty. Understanding the coefficient of variation is crucial for kanban sizing, as it helps in adjusting buffer levels and inventory management to account for demand variability, ensuring smoother operations and minimizing the risk of stockouts or overproduction.

5.2.1.3 *ABC-RRS Analysis*

Right after the analysis of consumption, it's time to interpret the data. As discussed in section 4.6.4, the ABC-RRS matrix plays a crucial role in categorizing items based on their economic value (ABC) and their usage frequency (RRS). By combining these two factors, the matrix provides a cross-category framework that helps determine the most appropriate codes for kanban implementation. In auxiliary, this scheme is used to effectively manage and classify different categories of items:

	Frequency		
Economic value	Runners	Repeaters	Strangers
A	kanban	kanban or MRP	MRP
B	kanban	kanban or MRP	MRP
C	double bin	double bin	double bin or MRP

Fig. 5-2 ABC-RRS categories management (auxiell, 2023)

For kanban system implementation, our focus typically starts with the A-Runners and B-Runners. These categories are particularly well-suited to the kanban philosophy because they represent items with high economic value and significant usage frequency. Essentially, these are codes with high turnover rates in the warehouse and are frequently used throughout the production process.

By considering the ABC-RRS matrix, auxiell can more strategically implement kanban systems, ensuring that inventory management aligns with both economic value and operational demand. This approach allows for a more targeted and efficient kanban setup, optimizing inventory levels and reducing waste.

5.3 Analysis of the new kanban formula

According to the needs of the company Acme Spa, my project is about analyzing a new method of pull system sizing in alternative to the classic kanban formula.

The necessity of studying a new method came from the need to provide a better service to clients by exploring the most effective ways to apply these techniques. Over time, it became clear that the classic formula, as mentioned in Chapter 4, was not sufficiently accurate when it came to determining average stock levels and the number of kanbans. Moreover, the assumptions used to select the appropriate service level and other variables did not always align with the actual situation. By factoring in more variables, it was evident that the average stock could be reduced, leading to greater economic savings and more efficient inventory management.

The need to explore a new approach came from the desire to offer a better service to our clients by finding the most efficient way to apply these techniques. To achieve this, I chose to adopt a

statistical method to analyze the new formula. This method allowed us to thoroughly assess the variables involved and ensure that the formula is optimized to maximize the service level, leading to better performance and greater savings before full implementation

5.3.1 Structure of the formula

The new formula for kanban sizing builds on the traditional approach but adds more depth with a three-step process. This helps in making the analysis more accurate and better suited to real-life situations.

The main change is how the analysis is broken down. Instead of just using a single method, the new formula divides the process into three distinct steps. Each step looks at different factors, which provides a clearer picture of how things work in practice.

The new formula has a single application but is interpreted differently depending on whether it's used for purchasing or production. In purchasing, the formula helps determine optimal order quantities by adjusting components based on lead times and lot sizes, ensuring the right balance of inventory. In production, it aids in scheduling and managing inventory, taking into account real-time stock levels and consumption rates. Instead of predicting demand, the formula adjusts for fluctuations and helps maintain a consistent flow, minimizing both excess stock and shortages.

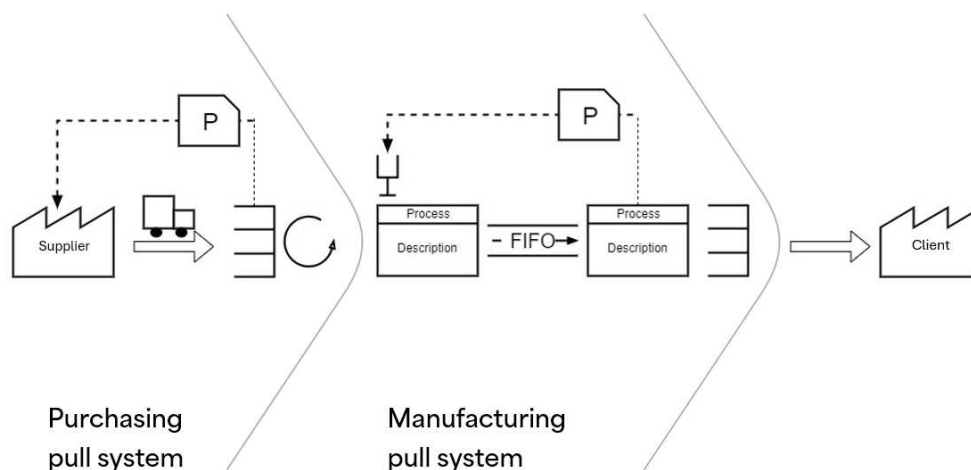


Fig. 5-3 Value stream map of the process

5.3.2 Purchasing Pull system

In the context of lean management, a purchasing pull system is essential for controlling inventory and reducing waste in the supply chain.

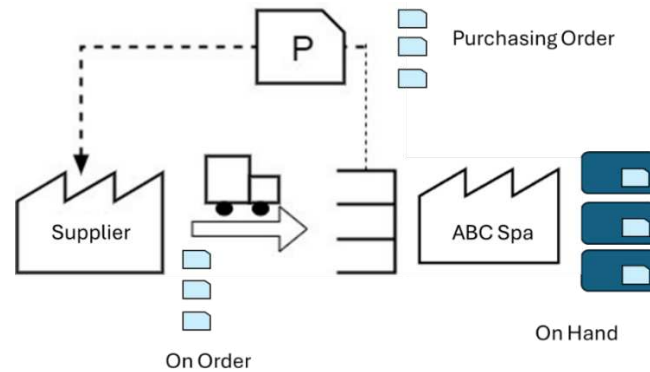


Fig. 5-4 Purchasing pull system

The process begins with an assessment of on-hand stock, as illustrated in the flowchart above. This stock is continuously monitored, and once it drops below a certain threshold, a purchasing order is triggered. As shown in the diagram, materials are replenished based on a clear flow from the warehouse to the supplier, ensuring that the right quantities are procured without overloading the warehouse.

This approach relies heavily on accurate data and the timely execution of purchasing orders. It also involves close coordination with suppliers to ensure materials are delivered within the required lead time.

In the next section, we will explore the structure of the kanban formula for purchasing, which includes steps to calculate reorder levels, manage lead times, and adjust for fluctuations in demand. The visual representation of the purchasing flow (Fig. 5.4) provides a clear understanding of how the kanban cards are used to manage inventory and trigger procurement actions.

The formula is composed by the following variables:

- Average demand (\bar{D}) [weekly/daily consumption]
- Standard deviation [same unit of measure of average demand]
- z coefficient: it is associated to the desired service level

- Order Frequency (OF): represents the frequency in days of sending the replenishment signal to the supplier. Typically represents a trade-off between minimum purchase lot required by the supplier and internal purchasing processes [pcs]
- Supplier Lead time (SLT): time between the order signal and the delivery of the order [pcs]



Fig. 5-5 Purchasing pull system

For simplicity, we can refer to this scheme as the "traffic light" system, as it functions in a similar way. Starting from the top, the Order Frequency stock (OFs) is the amount of stockpile that must be available in the warehouse to account for constraints in the purchasing or shipping process. It plays a critical role in ensuring the smooth operation of the inventory system. When the "green sector" (the OFs) is consumed, it signals that a new order must be triggered. Essentially, this quantity serves as the threshold, telling you it's time to reorder as soon as it is depleted. We can look at the scheme below to better understand the concept:

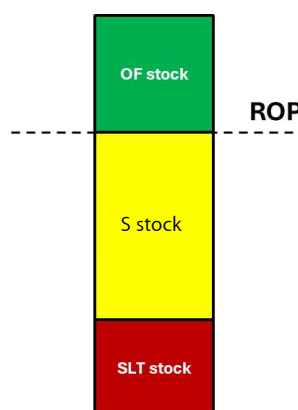


Fig. 5-6 Visual representation of the ROP

This is the formula for calculating it:

$$OF \text{ stock [pcs]} = \max[OF * \bar{D}; \text{minimum purchase lot}; SF * \bar{D}]$$

Where:

\bar{D} = average demand [pcs]

SF = supplier-performed shipment frequency

OF = order frequency [day or week]

OFs = order frequency stock [pcs]

Explained in words, it is represented by the maximum value between the frequency of sending the replenishment signal for the average demand, the minimum purchase lot (expressed in pieces), and the supplier-performed shipment frequency (SF) for the average demand.

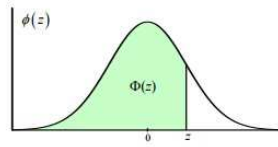
Moving into the red sector, the Supplier Lead Time Stock (SLTs) is the quantity of stock needed to cover the time required for internal purchasing and receiving processes, order entry, and the supplier's production lead time. In practice, this amount of stock will not physically be in the warehouse, but it's necessary to account for the time constraints mentioned. The formula to calculate the supplier lead time stock is:

$$SLT \text{ stock [pcs]} = SLT * \bar{D}$$

The yellow sector indicates the safety stocks (SS). They represent the excess stocks useful to overcome uncertainties of market demand, lead time variation and changes that occur in supply and quality problems. This formula is characterized by the service level “z¹²” which is defined based on the Gaussian distribution:¹³

¹² The service level is an important Key Performance Indicator (KPI) that, in simplified terms, measures a company's ability to fulfill customer demand. Higher is the level the company wants to guarantee, higher will be the amount of stocks to keep in the warehouse.

¹³ Gaussian distributions are one of the most important distributions in statistics. It is a continuous probability distribution that approximately describes some mass of objects that concentrate about their mean



z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706

Fig. 5-7 The table provides the value of the area under the standard normal distribution $f(z)$, between $-\infty$ and z

The formula to calculate the safety stocks is:

$$SS [pcs] = z * dev_{std} * (OF + SLT)^\beta$$

Where:

dev_{std} = standard deviation

β = it is usually 0.5, as suggested by the literature. However, as we will explore in the next paragraphs, other values may be more appropriate depending on specific situations.

Therefore, these three colors represent three different levels of stock, and summed together represent the maximum stock of material dimensioned.

$$Maximum\ stocks [pcs] = OFs + SS + SLTs$$

This approach provides a balanced system to manage inventory, minimize waste, and align stock levels with actual consumption.

5.3.3 Manufacturing Pull system

Moving into the production process, regulating the manufacturing system other variables to correctly dimension the stock levels between operations. This is essential to ensure a smooth flow of materials throughout the production stages.

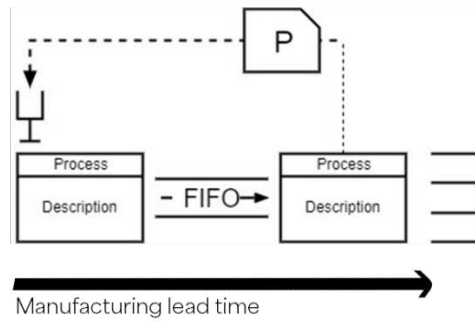


Fig. 5-8 Scheme of the manufacturing lead time

The variable considered in this environment are the same as the purchasing pull system except of the following:

- Cycle time interval (CTI): The cycle time interval stock is the amount of stock I need to hold to absorb the setup constraints of the production process. This value is closely related to production lot sizes based on EPEI¹⁴ or Product Wheel¹⁵.
- Manufacturing lead time (MLT): on the other hand, represents the total time it takes from triggering a replenishment request to having the product available again in stock for use.

It is calculated using the formula: $MLT [days\ or\ weeks] = \frac{WIP}{output}$

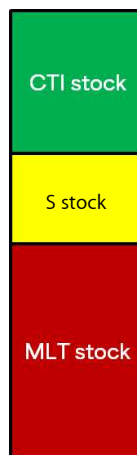


Fig. 5-9 Manufacturing pull system

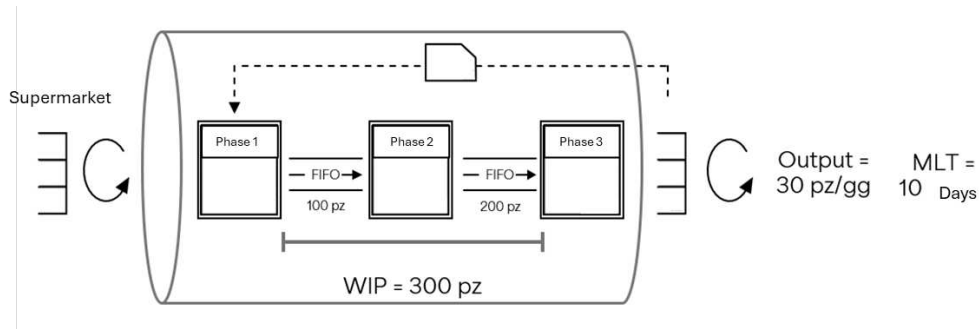
¹⁴ EPEI (Every Part Every Interval) is a lean manufacturing approach that schedules the production of each part at a consistent interval, helping to balance production and reduce waste (Schonberger, 1986)

¹⁵ A Product Wheel is a lean tool used to sequence different product runs in a cycle, minimizing changeover times and inventory, while maintaining regular production flow. (King, 2009)

Meanwhile, the manufacturing lead time stock (MLTs) is the quantity of stocks to keep in the warehouse to absorb the constraints of the production process lead time.

$$MLTs [pcs] = MLT * \bar{D}$$

Here's below is represented a scheme to better understand the concept of manufacturing pull system. There are some numerical examples to see how the formulas work:



Instead, the cycle time interval stock (CTIs) is the amount of stock that must be maintained in the warehouse to absorb the constraints associated with the production process setup. This value is closely related to production lot sizes.

$$CTI \text{ stock}[pcs] = CTI * \bar{D}$$

Additionally, the safety stock (SS) follows a similar calculation as in the purchasing pull system, but in this case, the lead time is composed of both the manufacturing lead time and the cycle time interval. The formula is:

$$SS [pcs] = z * dev_{std} * (MLT + CTI)^{\beta}$$

Finally, the total maximum stock level in the manufacturing pull system is obtained by summing the cycle time interval stock, safety stock, and manufacturing lead time stock:

$$Maximum \text{ stocks } [pcs] = CTI \text{ stock} + SS + MLT \text{ stock}$$

These components work together to ensure sufficient stock levels to absorb uncertainties in demand and production variability.

5.4 Preliminary analysis

Taking into consideration the new formula for kanban system sizing, especially on the purchasing side, my analysis started by developing a preliminary Excel model. This model was used to

simulate the consumption trend against the stock levels currently available in the warehouse, based on historical data, to check if the stock levels is appropriate.

The goal was to create a practical tool that could numerically show the trends, helping to visualize how consumption affects stock levels over time, either increasing or decreasing the overall inventory in the warehouse.

In the first table, you can see the item number followed by the consumption trend (in pieces) over the year, divided into weekly periods.

Table 5-1 Consumption matrix of Acme Spa

Items	202401	202402	202403	202404	202405	202406	202407	202408	202409	202410	202411	202412
3023073A	0	22065	22900	18797	27191	24460	32962	7380	23622	22780	23491	29000
2716198A	0	3000	4005	603	1370	4890	3923	5400	5417	4727	9260	3000
3023072A	3251	0	7540	4110	1200	0	13910	9270	652	50	9618	5000
3025028A	200	3017	504	1990	2280	0	7210	2316	4550	292	260	0
2613062B	23571	20117	23220	28661	24370	31853	26500	33582	26254	28961	38659	35000
3023091A	3300	3500	601	1300	744	0	2000	1	200	0	5700	0
2D.TRPDS.1000	4840	3386	4024	6002	3178	5614	5150	5556	4862	4489	5825	4000
5073500A	5800	4470	4200	2143	3000	3790	7800	7811	5070	4330	4300	5000
2716165A	3300	3502	601	1360	745	0	2000	250	2762	1600	6890	0
5533666B	5800	5005	4203	2383	3000	3790	7800	7829	6490	8890	4300	5000

In the second table, the stock levels in the warehouse are shown, again divided by week. To clarify, the simulation begins at day 0, which is the point when the analysis starts, reflecting the stock levels present at that time. From this data, weekly consumption is subtracted, following the trend outlined in Table 5-1. For each item, we then calculate the re-order point (ROP), which is the threshold that triggers a new order to replenish the stock. The ROP for each item is calculated using the following formula:

$$ROP = SS + SLTs$$

Where:

SS = Safety Stock

SLTs = Supplier Lead Time stock

Visually, the ROP is represented by the yellow and red parts of the "traffic light" diagram.

As previously discussed, the Order Frequency Stock (OFs) represents the quantity of stock that must be kept to account for variability or constraints in the purchasing and replenishment processes. This stock level is carefully calculated to ensure the production process runs smoothly. However, if demand fluctuates or there are supply issues, the "green sector" (the regular stock on hand) may not be enough to keep the flow uninterrupted. In such cases, it's essential to place orders in advance to maintain adequate stock levels and prevent a stockout. By setting the

reorder point strategically, the system can trigger new orders when the stock drops below this critical threshold. The goal is to prevent critical shortages that could disrupt production or increase costs through emergency orders.

The table below shows the amount of stock ordered.

Table 5-2 Re-ordered quantity

Items	202401	202402	202403	202404	202405	202406	202407	202408	202409	202410	202411	202412
3023073A	0	0	40400	0	45988	24460	32962	0	31002	22780	23491	29700
2716198A	0	0	0	0	0	7730	3923	5400	5417	4727	9260	39000
3023072A	3251	0	7967	4110	0	0	15110	9270	0	0	10320	57000
3025028A	200	0	0	0	2773	0	7210	2316	4550	0	0	0
2613062B	23571	0	39607	28661	0	56223	0	60082	0	55215	38659	35200
3023091A	3300	0	0	0	0	0	0	0	0	0	0	0
2D.TRPDS.1006	4840	9915	4024	6002	0	8792	5150	5556	4862	4489	5825	49000
5073500A	5800	0	8302	0	5143	0	11590	7811	5070	4330	4300	95000
2716165A	3300	0	0	0	0	0	2922	0	3012	0	8490	0
5533666B	5800	0	5028	0	5383	0	11590	7829	6490	8890	0	135000

Here's below, is displayed the table with the stock level.

Table 5-3 Stock level

Items	Day_0	202401	202402	202403	202404	202405	202406	202407	202408	202409	202410	202411	202412
3023073A	76739	76739	54674	31774	53377	26186	47714	39212	64794	41172	49394	48683	42000
2716198A	20625	20625	17625	13620	13017	11647	6757	10564	9087	9070	9760	5227	100000
3023072A	15531	12280	15531	7991	11849	14759	14759	849	6689	15307	15257	5639	100000
3025028A	16886	16686	13869	13365	11375	9095	11869	4659	9553	7319	11577	11317	100000
2613062B	84478	60907	64361	41141	52087	56378	24525	54248	20666	54494	25533	42089	450000
3023091A	22110	18810	18610	18009	16709	15965	15965	13965	13964	13764	13764	8064	700000
2D.TRPDS.1006	6743	1903	3357	9248	7270	10094	4480	8122	7716	8410	8783	7447	800000
5073500A	18531	12731	14061	9861	16020	13020	14373	6573	10352	13093	13833	13863	800000
2716165A	14013	10713	10511	9910	8550	7805	7805	5805	8476	5714	7126	236	700000
5533666B	23205	17405	18200	13997	16642	13642	15235	7435	11196	12535	10135	14725	500000

Excel was primarily used as a tool to formalize the initial database and serve as a support for early analysis. However, to improve efficiency and accuracy, we moved to a more robust method using Python. This allowed us to simulate stock trends more effectively, with selected outputs that better aligned with our analytical needs.

By using Python, we were able to overcome the limitations of Excel and streamline the entire simulation process. In the following chapter, we'll explore in detail how this statistical model enhanced our workflow and provided important insights.

5.5 Advanced analysis

By applying the new formula, particularly within the purchasing pull system and using the Acme Spa case study, we developed a Python model capable of simulating large datasets automatically and generating outputs to analyze real-world scenarios. The primary goal of this model is to numerically and graphically assess the results for each item code, identifying the best configuration of the formula based on the characteristics of demand and supply.

This analysis aims to minimize stock levels while maximizing service levels, as well as to identify common patterns that could be useful for improving value delivery in other clients or situations. Additionally, the model helps highlight both qualitative and quantitative benefits compared to the traditional formula.

5.5.1 Input data

I will start from the input database, to show what information do I need for this analysis.

Firstly, I need the consumption matrix of each item considered. In the table below, is displays the items number in the 1st column while the period of time is in the first raw always represented with the format yyyy+mm.

Table 5-4 Consumption matrix

	202401	202402	202403	202404	202405	202406	202407	202408	202409	202410	202411	202412	202413	202414
2716198A	0	3000	4005	603	1370	4890	3923	5400	5417	4727	9260	3970	8515	4810
3023072A	0	3251	0	7540	4110	1200	0	13910	9270	652	50	9618	5765	6290
3025028A	0	200	3017	504	1990	2280	0	7210	2316	4550	292	260	770	160
3023091A	0	3300	3500	601	1300	744	0	2000	1	200	0	5700	500	931
2D.TRPDS.1006	0	4840	3386	4024	6002	3178	5614	5150	5556	4862	4489	5825	4995	2947
5073500A	0	5800	4470	4200	2143	3000	3790	7800	7811	5070	4330	4300	9510	2875
2716165A	0	3300	3502	601	1360	745	0	2000	250	2762	1600	6890	770	0
5533666B	0	5800	5005	4203	2383	3000	3790	7800	7829	6490	8890	4300	9511	3925
2716284A	0	0	0	5400	10800	0	0	0	0	9720	4320	0	0	10800
2716287A	0	7560	4320	0	3240	11880	0	0	0	0	0	14040	12960	0
2828081A	0	8000	2466	1920	2000	1	5924	210	6	0	3535	3010	3094	2945
2D.TRPDS.1007	0	374	113	713	226	467	555	454	0	230	292	50	439	505

Table 5-5 Input data

code	SLT [wk]	OF [wk]	Maximum stocks [pcs]	Box size [pcs]	Minimum purchase lot [pcs]	Supplier shipment frequency [wk]
2716198A	1	1	14487	1600	1600	1
3023072A	1	1	18116	2040	2040	1
3025028A	1	1	13460	1440	1440	1
3023091A	1	1	8819	840	840	1
2D.TRPDS.1006	1	1	13272	3200	3200	1
5073500A	1	1	18163	864	864	1
2716165A	1	1	8726	1600	100	1
5533666B	1	1	19025	1020	1020	1
2716284A	1	1	23075	2520	2520	1
2716287A	1	1	21858	2520	2520	1
2828081A	1	1	14564	3200	3200	1
2D.TRPDS.1007	1	1	1370	800	100	1
2716154A	1	1	1463	400	100	1
2716162A	1	1	874	400	100	1
5920503C	1	1	17352	1600	1600	1

Starting from the left column, we have the item codes followed by the lead times, which are divided into Order Frequency (OF) and Supplier Lead Time (SLT). Together, they represent the total lead time required to supply materials in the worst-case scenario. In this context, using the Acme Spa case study as an example, we have scheduled kanban checks every Friday at midday. If an item reaches its reorder point after midday on a Friday, it must wait until the following Friday for a new order to be placed. In this situation, the item would need to wait through the entire order frequency (1 week) plus the supplier lead time (1 week), totaling 2 weeks.

Next, we see the stock level in its AS-IS state, essentially a snapshot of the company's current stock situation. This provides an exact record of how much stock each item has before we implement the kanban system. This data serves two key purposes: first, it acts as our starting point for simulating how stock levels will fluctuate by subtracting the weekly consumption. Second, it becomes a valuable reference point for the end of the analysis, where we can clearly see the tangible benefits of the kanban system.

From the client's perspective, this comparison between the "before" and "after" gives a clear view of how the kanban system works in practice. It shows how the system reduces inventory levels, freeing up warehouse space, and most importantly, reducing overall inventory costs. These benefits aren't just theoretical; clients can physically see how the system lowers stock levels and

streamlines their operations. And of course, with lower stock levels comes less risk of obsolescence and waste, which is another major advantage.

Right after that, I focused on adapting the simulation to reflect real-world scenarios. When working with external suppliers, communication can sometimes be challenging due to physical distances, differing policies, or even logistical constraints. Simply calculating kanban by focusing on stock quantities without considering these factors can lead to inaccuracies. If you overlook these variables, you might end up with stock levels that don't align with what can realistically be ordered.

Take the case of Acme Spa, for example. Their suppliers ship components on standardized Euro pallets. However, the quantity of stock that fits on a pallet differs for each item. This quantity is fixed, meaning you can't just order any exact number of items; you have to order based on the pallet or box size. As an input for the kanban calculation, we introduced the "box size" to represent the minimum quantity of items that can be ordered. This ensures that orders are placed in multiples of the box or pallet size, avoiding misalignments between inventory planning and actual supplier capabilities.

The last two outputs directly relate to the new formula for kanban sizing, with a focus on calculating the Order Frequency Stock (OFs). Determining OFs requires careful consideration of several constraints that may affect the ordering process. These typically include the minimum purchasing lot, which is the smallest quantity a supplier will accept in a single order; the supplier's shipment frequency, or how often they can deliver goods; and the order frequency, which refers to how often the company places orders with the supplier.

These constraints are important because they aren't easily adjustable in the short term. Typically, they require longer processes, like extended negotiations with suppliers, to reduce lead times or adjust minimum order quantities. This is why they're built into the kanban system to ensure stability while those longer-term improvements are worked on.

At Acme Spa, we initially faced long lead times, which were a challenge to manage. To improve the supply side, we took proactive steps by visiting suppliers and negotiating agreements to reduce replenishment lead times. This effort significantly increased the frequency of our orders. We went from having an average lead time of 50 days to just 5 days in the current system.

One of the key strategies we used to achieve this was the implementation of a "supermarket" at the supplier's warehouse. This allowed them to produce and stocking a predetermined quantity of

products. By reducing lead times, we delivered substantial improvements for Acme Spa in terms of stock levels, and inventory costs dropped dramatically.

In numbers, if we previously needed to stock enough inventory to cover 50 days of operations, today, that stock level is ten times lower. Beyond cost savings, this change also enhances the relationship between Acme Spa and its suppliers. By working closely together, they built a relationship of trust, where both parties are more interdependent and collaborative. In the long term, this creates a reliable and trusted supply chain, benefiting both Acme Spa and its suppliers.

5.5.2 Development and implementation process

Although the development of the kanban sizing model required specific programming skills, my main focus was on designing and using it effectively for kanban system sizing. I worked closely with a colleague to ensure the model accurately reflected real-life trends in stock levels, consumption, and orders.

The program was designed to automate key calculations, such as reorder points (ROP), safety stocks (SS), coverage ratio... using the data inputs detailed in the previous section. The statistical simulations generated by the program allowed us to test various scenarios, adjusting for factors like supplier lead times, minimum order quantities, and service levels.

The core objective of the model was to create a tool that could virtually simulate different scenarios by easily adjusting variables. We moved away from Excel because it was too time-consuming, while entering these variables into the program was much faster and reliable. The key variables we focused on were the service level and the lead time exponent, both of which are referring to the safety stock formula. These two factors were prioritized because, in practice, the desired service level is often not achieved, which can lead to either surplus stock or stock shortages.

In the next section, the outputs from these simulations are explained in detail.

5.5.3 Output data

After processing all the input data, the Python model generates an output in the form of an Excel sheet that is easy to interpret and, if necessary, adjust.

Table 5-6 Output data for item: 2716198A with service level of 99% and β (the exponent of the Lead Time in the safety stock formula) equal to 0,5

OUTPUT DATA					
Week	Weekly consumption [pcs]	Weekly stocks (p=0.99, $\beta=0.5$)	Re-order quantity (p=0.99, $\beta=0.5$)	Pending Orders (p=0.99, $\beta=0.5$)	Out of Stock (p=0.99, $\beta=0.5$)
202401	0	14487	0	0	0
202402	3000	11487	0	0	0
202403	4005	7482	6400	0	0
202404	603	13279	0	0	0
202405	1370	11909	0	0	0
202406	4890	7019	6400	0	0
202407	3923	9496	0	0	0
202408	5400	4096	9600	0	0
202409	5417	8279	4800	0	0
202410	4727	8352	4800	0	0
202411	9260	3892	9600	0	0
202412	3970	9522	0	0	0
202413	8515	1007	12800	0	0
202414	4810	8997	4800	0	0
202415	6231	7566	6400	0	0

This is one of the key outputs produced. It captures the stock movements within the warehouse, the corresponding orders, and the number of out-of-stock situations detected. Essentially, by following the data, we can see the initial stock level (AS-IS) of 14.487 pieces. In the next period (202402), a consumption of 3.000 pieces is registered, which is subtracted from the initial stock level. This process continues through each iteration until the stock level reaches the reorder point (ROP). At this stage, the available Order Frequency stock (the green part) has been finished.

Once the stock drops below the ROP, a new order is triggered to replenish the inventory. At this point, the system dips into the safety stock to maintain production flow. The reorder quantity is calculated based on the maximum stock level:

$$Reorder\ quantity_n = Maximum\ stock - weekly\ stock_n$$

To ensure that the calculations align with reality, the reorder quantity is rounded up based on the box size or minimum order size set by the supplier. In this example, the reorder quantity comes to 6.400 pieces, which helps to restore a safe stock level for the upcoming week.

The "Pending Orders" column in this example shows a value of 0, as we're working with a lead time of one week. In cases where the lead time is longer (e.g., more than one week), the orders placed will not arrive immediately. This column helps us keep track of orders that have been placed but have not yet arrived.

For example, if the lead time is four weeks, and an order is placed in week n , we know that it will arrive in week $n+4$. If another order is required in week $n+1$, we need to account for the order that is already on its way. In such cases, the reorder quantity will be calculated as follows:

$$Reorder\ quantity\ week_{n+1} = Max\ quantity - weekly\ stock_{n+1} - Reorder\ quantity\ week_n$$

This approach ensures that orders are placed accurately, avoiding both overstocking and stockouts, and optimizing inventory levels based on real-time conditions.

Lastly, the "Out of Stock" column displays how many times our inventory fails to meet market demand. This is a crucial metric, as it shows the moments where the stock level fell short, potentially leading to production delays or missed sales opportunities. By tracking this, we can identify weak points in the supply chain and adjust reorder quantities or lead times to better align with actual consumption patterns, ultimately reducing the risk of stockouts in the future.

Table 5-7 Output data for item: 2716198A

Theoretical Service Level	0,99	0,8
Beta	0,5	0,5
Average stocks [pcs]	9048	5754
Coverage Ratio [wk]	2,7	1,7
Service Level	100%	97,06%
Safety Stock [pcs]	6002	2172
ROP [pcs]	9356	5526
Variation Coefficient	0,77	0,77
Normality	FALSE	FALSE
P-value	0,0178109	0,0178109
#KB	8	6
Maximum stock [pcs]	12711	8881

This is the second table generated as output. At the start, it presents two different scenarios: the left-hand side shows the case where a service level of 99% is assumed, while on the right-hand side, a more conservative service level of 80% is considered. The comparison of these two service levels helps in understanding how stock levels and reorder points fluctuate based on the desired reliability of meeting demand.

Next, there is the β factor, which was introduced to give more flexibility in adjusting the safety stock formula. This variable allows us to modify the system by adjusting two key factors: the variability in lead time and demand fluctuations. In this example, we simulate a standard scenario where $\beta=0.5$, which is commonly used in literature to strike a balance between stock security and cost.

The real value of this project lies in its ability to adjust variables like β and service levels, making the model adaptable to real-life situations. By running multiple simulations with different values, we can create various potential scenarios. This flexibility is incredibly helpful as it allows the company to choose variables based on real data, testing their system under different demand

patterns or supplier lead times. Based on past data, the simulation can show whether the stock level is likely to enter a critical situation (stockout) or whether it remains appropriate for the expected market demand.

Continuing with the analysis, we come to two essential metrics: average stock and maximum stock. These figures are critical for effective inventory management. The average stock indicates the typical amount of inventory held in the warehouse over time. By dividing this quantity by the box or pallet size, you can easily calculate how much physical space, in terms of spots or slots, you will need in the warehouse to store these items.

On the other hand, the maximum stock represents the highest level of inventory planned for each item. This figure is particularly important when implementing a kanban system because it helps determine the number of kanban cards required. The maximum stock is calculated by multiplying the number of kanban cards by the quantity stored in each box or pallet. However, it's important to note that, in a properly functioning kanban system, this maximum stock will rarely, if ever, be present in the warehouse all at once. The system is designed to keep inventory flowing efficiently, so you will typically only hold part of this total at any given time.

The reorder point (ROP), as already mentioned, is calculated by the sum of SLT's plus the SS and represents the threshold after which an order must be placed. Connected to the reorder point there are two different modus operands. Company can decide to use a scheduled check of inventory or a continuous check of it. For instance, at Acme Spa, we implemented the former process by checking the kanban board every Friday at midday. If any component reached the yellow sector (safety stock), a new order would be triggered to replenish the inventory.

The coverage ratio is calculated using the following formula:

$$\text{Coverage ratio} = \frac{\text{average stocks}}{\bar{D}}$$

Where:

\bar{D} =average consumption

It provides an estimate of how long, in weeks, the current average stock will last if there is a disruption in supply. In our case study, for item 2716198A, using the variables selected to achieve a 99% service level, the coverage ratio suggests that the stock can sustain production for about 2.7 weeks. However, it's important to keep in mind that this is just an estimate. If market demand

fluctuates, which is highly likely, the actual coverage period could be longer or shorter depending on the nature and extent of the changes in demand.

The service level shown in the table is essentially a percentage that represents how effectively the system meets production demand without causing a stockout. It is calculated by considering how often the system fails to supply enough stock to meet production needs. This percentage is derived by counting the total number of times a stockout happens over the period being analyzed and comparing it to the total number of weeks considered.

For example, if out of 52 weeks, the system experiences stockouts in 5 weeks, the service level would be calculated as:

$$\text{Service level} = \left(\frac{52 - 5}{52} \right) * 100 = 90.38\%$$

This means that in 90.38% of the time, the system was able to fulfill production requirements without stockouts, offering a clear view of how often the inventory system effectively supports production.

A more statistical variable we considered is the normality of the distribution. This information helps improve the analysis by giving insights into the consumption trend. When dealing with a normal distribution, the consumption trend is generally more predictable, which reduces the margin of error in estimates and calculations.

To check the normality, I use the Shapiro-Wilk test. A statistical test used to assess whether a dataset follows a normal distribution. Specifically, it checks if the data's distribution differs significantly from a normal distribution. A p-value is generated from the test: if the p-value is less than a chosen significance level (typically 0.05), the null hypothesis that the data is normally distributed is rejected.

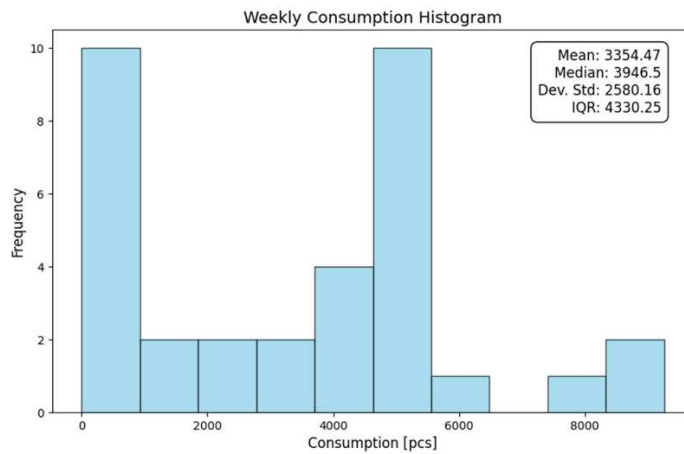
This test is widely used because of its effectiveness in detecting deviations from normality, particularly with small sample sizes (Shapiro & Wilk, 1965).

To support this analysis, we also included a histogram in the output. This histogram visually represents the distribution of the consumption data, making it easier to observe patterns or deviations from normality. By comparing the shape of the histogram to a standard normal distribution curve, we can quickly assess whether the data follows a predictable trend or if there

are significant fluctuations that might require further investigation or adjustments in the kanban system. The histogram adds a practical visual aid to complement the Shapiro-Wilk test results.

In our example, the consumption for the item considered does not follow a normal distribution.

Table 5-8 Histogram of consumption item: 2716198A



Finally, I introduced a visual representation of the overall simulation, showing important insight directly into the graph.

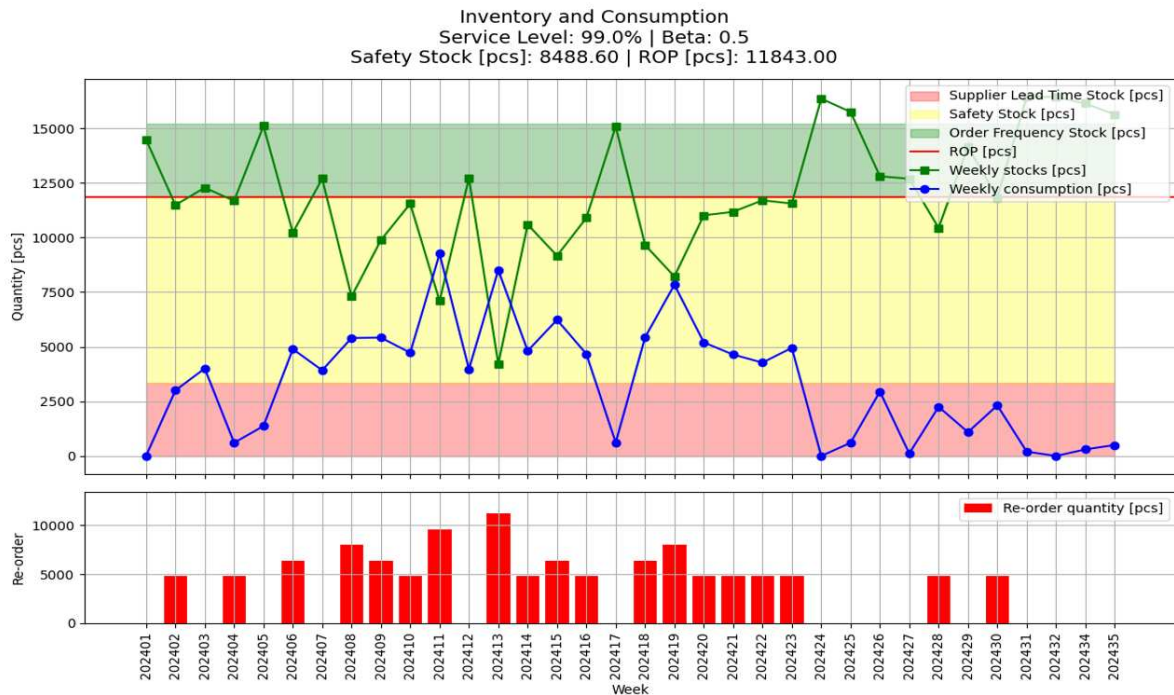


Fig. 5-10 Visual representation item 2716198A

The chart summarizes the inventory and consumption dynamics over time based on the parameters defined for the scenario. At the top, key metrics such as service level (99%), β (0.5), safety stock, and reorder point (ROP) are provided to contextualize the graph.

- Green Line (Weekly Stocks): This line tracks the stock level for each week, starting from the initial stock (AS-IS). The stock level fluctuates as items are consumed and replenished over time.
- Blue Line (Weekly Consumption): This line shows the trend of weekly consumption, following the patterns analyzed in the ABC matrix. The consumption fluctuates based on the demand for the product.
- Red Line (Reorder Point): The red line indicates the reorder point (ROP). Every time the green line (stock level) dips below this red line, an order is triggered.
- Red Bars (Reorder Quantity): Below the main graph is the red bar chart representing the reorder quantities for each week. Each bar corresponds to an order placed by the company, which, in this scenario, is delivered the following week.

This visual representation helps in understanding how the kanban system manages inventory, when reorder points are reached, and how frequently orders are triggered based on stock levels.

In conclusion, the outputs analyzed provide a comprehensive understanding of how the kanban system operates in managing inventory, addressing fluctuations in consumption, and optimizing stock levels. The detailed analysis of the reorder points (ROP), safety stock, coverage ratios... demonstrates how the system maintains balance between production needs and supply capabilities. The comparison between different service levels (99% vs. 80%) highlights the impact of desired service levels on stock requirements and the ability to respond to market demands.

By using the statistical simulations and adjusting key variables such as β , lead times, and service levels, we can gain a more accurate picture of how the system performs in various scenarios. The flexibility provided by the model allows for the testing of different consumption trends, supplier lead times, and order frequencies. As evidenced in the case of Acme Spa, these outputs offer critical insights into stock movements, lead times, and reordering strategies, ultimately leading to cost reductions and improved efficiency.

The visual output, further clarify the relationship between stock levels, consumption patterns, and reorder triggers. The inclusion of variables such as the normality of distribution using the

Shapiro-Wilk test supports a more precise calculation of demand trends, further reducing the margin of error in predictions. Ultimately, this analysis underscores the effectiveness of the kanban system in maintaining optimal stock levels, avoiding stockouts, and preventing excessive overstock, ensuring a smoother and more cost-efficient operation.

5.6 Synthesis

To summarize all this information, the following two tables present the input data used for the calculations and the corresponding output generated.

Table 5-9 input variables

INPUT				
<i>Consumption matrix</i>				
+				
<i>code</i>	<i>OF [wk]</i>	<i>SLT[wk]</i>	<i>Maximum stocks [pcs]</i>	<i>Box size [pcs]</i>
<i>Minimum purchase lot [pcs]</i>	<i>Supplier shipment frequency [wk]</i>		<i>Theoretical Service Level</i>	<i>Beta</i>

Table 5-10 output variables

OUTPUT					
<i>SLT stocks [pcs]</i>	<i>OF stocks [pcs]</i>	<i>Average stocks [pcs]</i>	<i>Coverage Ratio [wk]</i>	<i>Service Level</i>	<i>Maximum stock [pcs]</i>
<i>Safety Stock [pcs]</i>	<i>ROP [pcs]</i>	<i>Variation Coefficient</i>	<i>Normality</i>	<i>P-value</i>	<i>#KB</i>

I included the variables "theoretical service level" and " β " in the input table because these are the key variables to adjust when changes are necessary. For instance, when evaluating a scenario where the average stock is higher than required, adjustments can be made by analyzing factors such as the normality of the distribution or the coefficient of variation. By modifying these variables, the inventory level can be aligned with the required service level, ensuring optimal stock management.

6 Final consideration

The purpose of implementing this new formula and developing the model is straightforward: to determine the optimal stock level that minimizes inventory costs while improving the efficiency of the replenishment process. Furthermore, it plays a crucial role in reducing incomprehension and inefficiencies when using the kanban system, ensuring that decisions are data-driven and processes run smoothly.

By calculating kanban system sizing through this method, the results are not only more precise but also offer actionable insights. These insights enable businesses to better manage their inventory, reduce waste, and enhance their operations. The real strength of this approach lies in its ability to simulate various market scenarios and consumption trends, providing decision-makers with a clearer picture of what adjustments can be made in real-time. This approach improves responsiveness, ensuring that stock levels align with fluctuating demand while keeping inventory costs at a minimum.

Here's below a comparison is demonstrated.

6.1 Comparison between the standard formula and the new formula

In this section, I will focus on comparing the traditional formula with the new one to highlight their respective pros and cons. The traditional formula, as explained in detail in *paragraph 4.4*, serves as the basis for this comparison. By examining the calculations, we aim to showcase the differences in how each formula handles key variables like stock levels, order frequencies, and safety stock requirements.

We will start with the same dataset for both formulas, ensuring that identical parameters are applied to make the comparison as fair and clear as possible. This side-by-side analysis will help demonstrate where the new formula improves accuracy, reduces costs, or offers better flexibility compared to the traditional approach. Through this, we can better understand the benefits and limitations of each method.

6.1.1 Traditional formula

Table 6-1 Input data for the traditional formula

code	LT [wk]	LTs [wk]	Box size [pcs]	Maximum consumption [pcs]	Average consumption [pcs]	#KB	#KB'	Dev std	SS [pcs]
2716198A	1	1	1600	8076	3354	12	3,10	2619,0	14246
3023072A	1	1	2040	9392	2684	11	2,32	3566,0	17716
3025028A	1	1	1440	8235	922	13	1,64	2828,2	16358
3023091A	1	1	840	5073	1713	14	3,04	1816,2	9207
2D.TRPDS.1006	1	1	3200	5887	3883	5	2,21	1853,9	8917
5073500A	1	1	864	9832	4217	24	5,88	3276,2	15655
2716165A	1	1	400	4571	1739	24	5,35	1767,4	7461
5533666B	1	1	1020	9833	4571	21	5,48	3327,4	15829
2716284A	1	1	2520	14418	3453	13	2,37	5373,9	26787
2716287A	1	1	2520	12961	4473	12	2,78	4963,9	23247
2828081A	1	1	3200	8277	955	7	1,30	2795,5	18245
2D.TRPDS.1007	1	1	800	703	477	3	1,60	223,2	1123
5920503C	1	1	1600	8119	6391	12	4,99	2609,4	11209
5920564C	1	1	280	1086	607	9	3,17	298,5	1633
5920505C	1	1	1600	3492	1706	6	2,07	1293,6	6294
3023073A	1	1	2028	31936	21995	33	11,85	9489,7	42901
3023093A	1	1	720	3565	988	11	2,37	1247,1	6212
3023075A	1	1	1728	1539	243	3	1,14	946,4	3213
3023074A	1	1	1872	1463	252	3	1,13	826,0	3492
2828019A	1	1	3200	4654	854	4	1,27	1646,2	8746
5523522B	1	1	1760	6172	2376	9	2,35	2332,1	11704

From this calculation, we obtained crucial metrics: the maximum stock and the average stock. These figures are essential for demonstrating the tangible improvements achieved for the final client. By presenting these metrics, we can show the effectiveness of the new formula in optimizing inventory management.

The formulas I used to get these values are explained in *section 4.4*. To calculate the maximum stock, we multiply the number of kanban cards (#KB) by the size of each box. While we use the following formula to compute the average stock:

$$\text{Average inventory level} = \left(\left[\frac{C_{max} * (LT + LT_s)}{Q} \right] - \frac{C_{avg} * LT_R}{Q} \right) * Q + \frac{Q}{2}$$

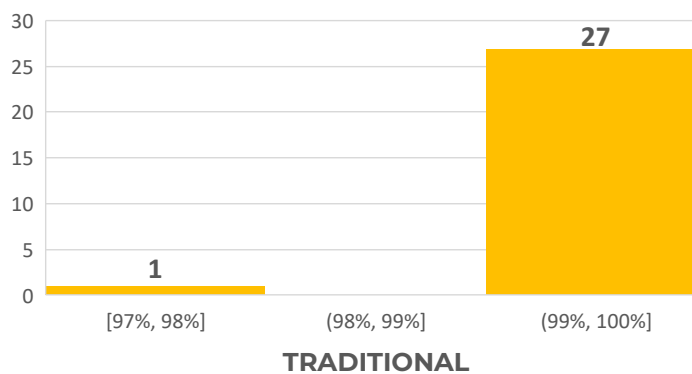
Then multiplying the maximum stock and the average stock for the unitary value of each item we obtain the maximum inventory cost and average inventory cost related to the items considered.

Table 6-2 Maximum and average inventory cost

code	Maximum stock [pcs]	Average stock [pcs]	Unitary value [pcs]	Maximum stock [€]	Average stock [€]
2716198A	19200	15046	4,80 €	92.200,32 €	72.250,14 €
3023072A	22440	18736	3,38 €	75.838,22 €	63.320,28 €
3025028A	18720	17078	4,68 €	87.602,11 €	79.919,25 €
3023091A	11760	9627	6,60 €	77.638,34 €	63.559,40 €
2D.TRPDS.100	16000	10517	2,51 €	40.112,00 €	26.366,27 €
5073500A	20736	16087	1,99 €	41.208,65 €	31.970,16 €
2716165A	9600	7661	4,74 €	45.489,60 €	36.303,32 €
5533666B	21420	16339	1,47 €	31.433,85 €	23.976,92 €
2716284A	32760	28047	1,68 €	55.056,46 €	47.136,46 €
2716287A	30240	24507	1,67 €	50.606,64 €	41.012,18 €
2828081A	22400	19845	0,79 €	17.635,52 €	15.624,36 €
2D.TRPDS.100	2400	1523	2,91 €	6.984,48 €	4.432,74 €
5920503C	19200	12009	0,10 €	2.000,64 €	1.251,38 €
5920564C	2520	1773	0,39 €	974,48 €	685,46 €
5920505C	9600	7094	0,15 €	1.400,64 €	1.034,95 €
3023073A	66924	43915	2,99 €	199.794,91 €	131.102,44 €
3023093A	7920	6572	6,62 €	52.392,38 €	43.476,07 €
3023075A	5184	4077	4,96 €	25.733,89 €	20.239,89 €
3023074A	5616	4428	4,94 €	27.740,23 €	21.872,15 €
2828019A	12800	10346	0,84 €	10.753,28 €	8.691,81 €
5522522B	15840	12584	0,11 €	6.518,16 €	5.178,28 €
			TOT.	991.179,85 €	770.697,88 €

The service level obtained is:

Table 6-3 Real service level registered using the traditional formula



6.1.2 New formula

With the new formula, the calculations follow exactly the steps outlined in Section 5.3.2. Using the model, we generated the entire dataset, making the calculations much faster and less time-

consuming. The maximum stock was calculated as the sum of the Order Frequency stock (OFs), the Supplier Lead Time stock (SLTs), and the Safety Stock (SS). Meanwhile, the average stock level was determined using the following formula:

$$\text{Average stock} = \frac{OFs}{2} + SS$$

Table 6-4 Input data and calculation of OFs, SLTs and SS

code	SLT [wk]	OF [wk]	SF [wk]	Average consumption [pcs]	Box size [pcs]	z (99%)	Minimum purchase lot [pcs]	Unitary value [pcs]	Dev.std	OFs [pcs]	SLTs [pcs]	SS [pcs]
2716198A	1	1	1	3354	1600	2,1	1600	4,80 €	2619,0	3354	3354	7778
3023072A	1	1	1	2684	2040	2,1	2040	3,38 €	3566,0	2684	2684	10591
3025028A	1	1	1	922	1440	2,1	1440	4,68 €	2828,2	1440	922	8399
3023091A	1	1	1	1713	840	2,1	840	6,60 €	1816,2	1713	1713	5394
2D.TRPDS.1006	1	1	1	3883	3200	2,1	3200	2,51 €	1853,9	3883	3883	5506
5073500A	1	1	1	4217	864	2,1	864	1,99 €	3276,2	4217	4217	9730
2716165A	1	1	1	1739	400	2,1	100	4,74 €	1767,4	1739	1739	5249
5533666B	1	1	1	4571	1020	2,1	1020	1,47 €	3327,4	4571	4571	9882
2716284A	1	1	1	3453	2520	2,1	2520	1,68 €	5373,9	3453	3453	15960
2716287A	1	1	1	4473	2520	2,1	2520	1,67 €	4963,9	4473	4473	14742
2828081A	1	1	1	955	3200	2,1	3200	0,79 €	2795,5	3200	955	8302
2D.TRPDS.1007	1	1	1	477	800	2,1	100	2,91 €	223,2	477	477	663
5920503C	1	1	1	6391	1600	2,1	1600	0,10 €	2609,4	6391	6391	7750
5920564C	1	1	1	607	280	2,1	280	0,39 €	298,5	607	607	887
5920505C	1	1	1	1706	1600	2,1	1600	0,15 €	1293,6	1706	1706	3842
3023073A	1	1	1	21995	2028	2,1	2028	2,99 €	9489,7	21995	21995	28183
3023093A	1	1	1	988	720	2,1	720	6,62 €	1247,1	988	988	3704
3023075A	1	1	1	243	1728	2,1	1728	4,96 €	946,4	1728	243	2811
3023074A	1	1	1	252	1872	2,1	1872	4,94 €	826,0	1872	252	2453
2828019A	1	1	1	854	3200	2,1	1600	0,84 €	1646,2	1600	854	4889
5523522B	1	1	1	2376	1760	2,1	110	0,41 €	2332,1	2376	2376	6926

Table 6-4 outlines the input data and calculations for OFs, SLTs, and SS. Based on this data, we calculated both the maximum and average stock levels and assessed their economic value.

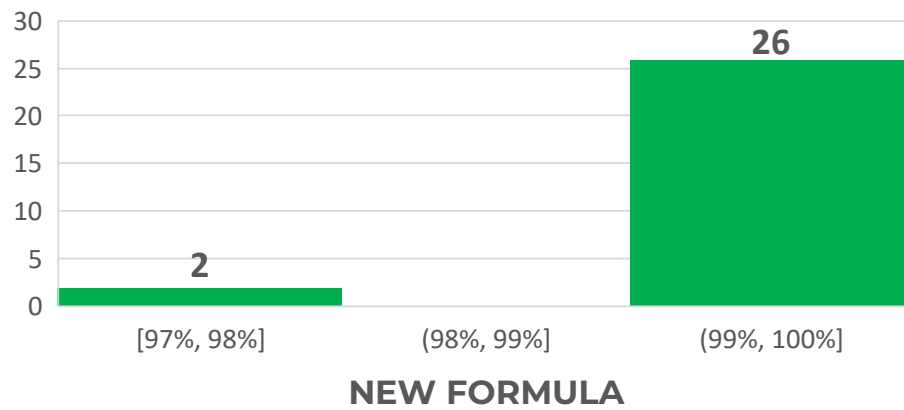
Table 6-5 Maximum and average inventory cost

le	Maximum stock [pcs]	Average stock [pcs]	Maximum stock [€]	Average stock [€]
2716198A	16000	9455	76.833,60 €	45.404,57 €
3023072A	18360	11933	62.049,46 €	40.327,25 €
3025028A	11520	9119	53.908,99 €	42.675,11 €
3023091A	10080	6250	66.547,15 €	41.262,53 €
2D.TRPDS.1006	16000	7447	40.112,00 €	18.670,20 €
5073500A	19008	11838	37.774,60 €	23.526,00 €
2716165A	9200	6118	43.594,20 €	28.990,89 €
5533666B	20400	12168	29.937,00 €	17.855,86 €
2716284A	25200	17686	42.351,12 €	29.723,28 €
2716287A	25200	16979	42.172,20 €	28.413,63 €
2828081A	12800	9902	10.077,44 €	7.795,99 €
2D.TRPDS.1007	2400	901	6.984,48 €	2.622,68 €
5920503C	20800	10945	2.167,36 €	1.140,46 €
5920564C	2520	1190	974,48 €	460,29 €
5920505C	9600	4695	1.400,64 €	685,00 €
3023073A	73008	39181	217.958,08 €	116.969,73 €
3023093A	6480	4197	42.866,50 €	27.767,19 €
3023075A	5184	3675	25.733,89 €	18.241,68 €
3023074A	5616	3389	27.740,23 €	16.740,89 €
2828019A	9600	5689	8.064,96 €	4.779,21 €
5572577B	11080	8111	5.702,07 €	2.228,80 €
		TOT.	880.869,93 €	530.955,94 €

These calculations allow for a direct comparison between the traditional and new formulas, showing not only improvements in stock management but also significant cost reductions. The new formula consistently led to a decrease in stock quantities (with some minor exceptions) compared to the traditional method. As a result, the service level achieved with the new formula is optimal.

The service level for the new formula was calculated using the Python model, which simulates consumption patterns and monitors how frequently the inventory fails to meet demand. The results demonstrate that the new formula allows for more precise stock sizing, ensuring a service level that consistently meets customer expectations with optimal stock quantities. This balance reduces excess inventory while still meeting demand, improving both customer satisfaction and operational efficiency.

Table 6-6 Real service level registered using the new formula with a probability of 99%



This approach ensures that inventory levels remain aligned with real-world consumption trends, reducing the risk of stockouts while optimizing costs. By fine-tuning variables, the model enables a more adaptable and efficient pull system, offering tangible benefits in both service level performance and inventory cost management.

6.2 Conclusion

To conclude the project of this master thesis, I will compare the results of the new and old formulas for kanban sizing, focusing on improvements in stock management and cost savings. The aim is to demonstrate how the new approach leads to more efficient inventory control and reduces costs thanks to its flexibility.

By guaranteeing the same service level, the comparison is based on two main factors: stock levels and financial impact. The former refer to both the maximum and average quantities held in inventory, which directly influence operational efficiency. The latter is measured through the cost savings achieved by reducing excess inventory and optimizing storage.

From the results obtained, it becomes evident that the new formula significantly outperforms the traditional one. The improvements can be seen in both the maximum stock held at any given time and the average stock maintained throughout the process. This reduction in stock levels translates into tangible economic benefits, with less capital occupied in inventory and lower associated costs such as storage and handling:

Table 6-7 Results' comparison between the traditional formula and the new formula

	Maximum stock [pcs]	Average stock [pcs]	Maximum stock [€]	Average stock [€]
TRADITIONAL	429.048	330.922	991.179,85 €	770.697,88 €
NEW FORMULA	380.952	224.263	880.869,93 €	530.955,94 €

The improvements are evident in the results. By switching to the new pull system sizing formula, the inventory costs for the items analyzed show a reduction of approximately 100.000 euros in the maximum inventory level. However, the most significant improvement is seen in the average stock: the quantity typically presents in the warehouse, where savings amount to around 250,000 euros.

Additionally, the new formula provides greater flexibility in adjusting key variables, such as service level and the lead time coefficient (β) in the safety stock formula. These adjustments can be made with greater confidence by thoroughly analyzing each specific scenario using the Python model, which allows for visual interpretation through graphs or by directly reviewing numerical outputs. Key outputs like the coefficient of variability (CV) or the normality of the distribution offer important insights. For example, an item with a CV of less than 1 and a normal distribution

is more stable and predictable over time. In contrast, an item with a higher CV and a non-normal distribution requires more conservative management, with higher stock levels to account for potential fluctuations.

Moreover, categorizing stock levels using the “traffic light” system provides a clear visual tool for prioritizing improvement actions. This approach allows the team to focus improvement actions on specific areas that need immediate attention, optimizing inventory management by addressing the most critical issues first.

Overall, these tools and analyses demonstrate how the new formula, together with the Python model, leads to significant improvements in inventory management and cost savings by better aligning stock levels with real market conditions. However, the true strength of this method lies in its ability to drill down into individual items, focusing on specific variables. This adaptability makes the new formula highly effective in managing complex, variable-driven scenarios, offering a major advantage over traditional methods.

6.3 Future initiatives

After having demonstrated the benefits of the new method, the next step is to develop a robust tool that can automatically calculate and simulate the variables analyzed in this thesis. The goal is for this model to be adopted as the new standard for kanban sizing at auxiell, making it accessible to the entire team. This tool will be designed not only for ease of use but also for accuracy, reducing the chances of errors in application.

To ensure the model’s reliability, it must be rigorously tested using real datasets from auxiell’s diverse range of clients. By analyzing data from different industries and varying demand patterns, the tool can be refined to account for specific client needs, further improving its functionality. This testing phase will also include statistical validation to confirm that the model consistently produces accurate and actionable results. Additionally, it is crucial to identify any unique variables or constraints that may affect kanban sizing in different environments, enabling continuous adjustments and enhancements to the tool.

In the long term, this tool will not only serve as a standard within auxiell but also offer the potential for broader applications in various industries. Clear guidelines and user-friendly instructions will be provided to ensure consistent use across the team, minimizing the risk of

mistakes. Future initiatives could focus on further automating the model, integrating machine learning to improve predictions, and expanding its use for more complex supply chain scenarios. Ultimately, this tool will serve as a reliable asset for optimizing inventory levels, driving cost efficiency, and supporting lean transformations in a wide range of companies.

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