Chapter 4
Pull Production Systems:
Link Between Lean Manufacturing and PPC

Eduardo Guilherme Satolo
https://orcid.org/0000-0002-8176-2423
São Paulo State University (UNESP), Brazil

Milena Estanislau Diniz Mansur dos Reis
https://orcid.org/0000-0003-1080-8735
Federal University of Rio de Janeiro (UFRJ), Brazil

Robisom Damasceno Calado
Fluminense Federal University (UFF), Brazil

ABSTRACT

This chapter aims to organize knowledge about pull production systems by presenting the underlying concepts of lean manufacturing as for its origin, principles, and relations with PPC. Pull production is one the fundamental principles of lean manufacturing, and its implementation can bring positive impacts. For such a purpose, sequential and mixed supermarket pull systems stand out in which the integration between pull production systems and PPC and its various levels is a main subject of discussion. The JIT model or Kanban method and hybrid systems, such as conwip and lung-drum-string theory, are mechanisms for managing pull production systems. Finally, a pull production system implementation is presented for illustration purposes. At the end of this chapter, it is expected that skills are developed by readers, which are going to assist them in using the tools presented to model production systems and aid decision-making processes.

DOI: 10.4018/978-1-7998-5768-6.ch004

INTRODUCTION

Lean Manufacturing Principles

The concept of Lean Manufacturing had its inception during the post-World War II period in Japan in the 1940s. At that time, the Toyota Company was experiencing difficulties due to economic and social issues that plagued the country. To rebuild itself, Toyota set out to rethink its production model and reinvent the means of production.

For such an end, it was determined that its manufacturing process would not be carried out through push production, as in mass production. In a production strategy called pull system, Toyota starts manufacturing only the number of items necessary to meet the customer's demand now of need by seeking excellence in manufactured items. At this point, to support this new way of thinking about production, principles and tools have been created over the years, which guided the creation of the Toyota Production System (STP).

Its success was not only due to economic terms, but also to quality, reliability, competitive prices, and the wide operational margin achieved by Toyota, which aroused curiosity and revealed the need for studies aimed to understand this new production method that culminated in incursions into Japan. One of the most notorious studies about it was conducted by Professors James Womack, Daniel Jones and Daniel Ross (1980s) on a research project at the Massachusetts Institute of Technology - MIT. This research aimed to study the global automobile industry by focusing on a comparison between European, American, and Japanese industries. The results obtained using the Japanese model by Toyota have been mapped through interviews involving employees, union members and government officials, which were highlighted as the best practices in the sector.

However, Womack el al. (1990s) published a book entitled "The machine that changed the world" in the 1990s, and a new philosophy has been extensively disseminated henceforth. In this book, the authors coined the term "Lean Production", which is considered synonymous with the term "Toyota Production System". This book served as reference for production management development in several other types of organizations.

As the theme started to become more deeply explored, Womack and Jones (1996) compiled a book called "Lean thinking - banish waste and create wealth in your corporation", which became a guide for the adoption of the lean philosophy by companies. Lean thinking is a management philosophy which is also described as an approach with which organizations develop skills towards gradually eliminating waste and creating value.

Since then, Lean manufacturing has been successfully disseminated and applied in different sectors of the economy and it has been named specifically according to its application area: lean education, lean public, lean healthcare, lean agrifood, and lean construction. However, its essence and principles remained unchanged.

Lean Manufacturing involves more than just eliminating waste, and it has five guiding principles, which are: value, value chain, continuos flow, pull production and perfection. The steps regarding these principles are going to be described as follows.

The 1st principle is to define value of given product in Lean Manufacturing from the customer's perspective, which is its first step. It is important that an organizational culture is established within the organization, which comprise predominant attitudes and behaviors that characterize the functioning of a group or organization, from the perspective of lean thinking associated with management commitment on strategic, tactical, and operational levels.

Understanding the current stage of the product within its life cycle, i.e., introduction, growth, maturity or decline, demand behavior, and order volumes is essential. Establishing the product value perceived by customers is associated with constant studies and a refined perception about changes in the customer's behavior that indicate the need for improvements.

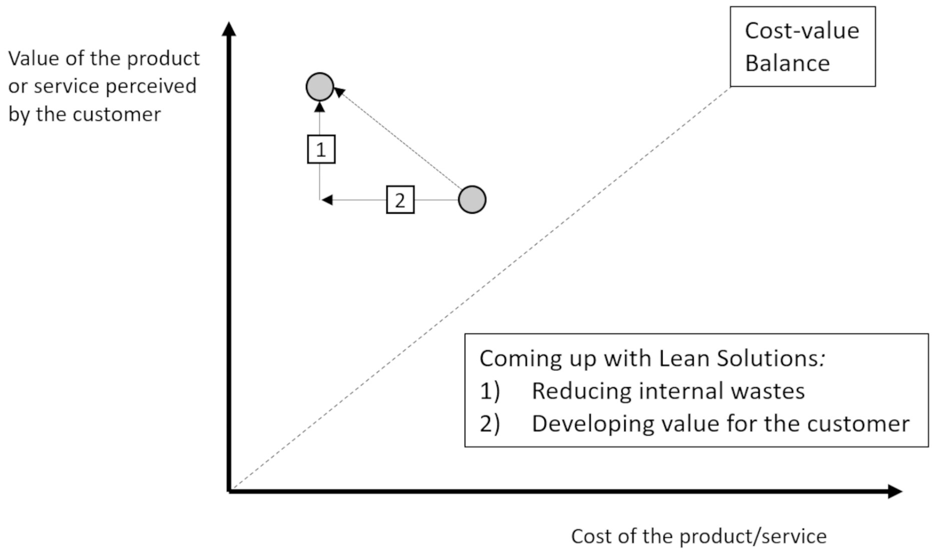
The second step to determine value is to calculate the target cost of a product based on resources and efforts required to produce it by eliminating waste. When the value of a product is exactly the price a customer is willing to pay (product cost), a cost-value balance is achieved, as shown in Figure 1. Value is increased when something, such as a resource or a service, is offered and valued by the customer, e.g., when there is faster delivery. A reduction in activities that do not add value to their costs also creates value.

The value chain, which is the 2nd principle, involves actions from conception to launch, i.e., the transformation of raw material into a finished product, from sale to delivery, in short, all activities involved in the creation of a finished product. The importance of identifying the value chain of a product or product family provides a distinction between steps that add value and those that do not, in addition to allowing effective actions that focus on a subsequent elimination of waste.

The value chain is designed by value stream mapping – VSM, which, visually represents the stream of materials using symbols and the flow of information within an organization to reproduce its current state and forecast its future state to indicate the path that a particular business is taking.

Along with the value stream mapping, performance indicators associated with cost, time, quality, and flexibility are calculated, for example: cycle time, value-added and non-value-added time, setup time, availability and number of operators, scrap rate, and lead time of activities that add value and of those that do not.

Figure 1. Relation among value, cost, and waste



For calculating these indicators, standardization is essential, since it is only through stable processes that a study on improvements is started. The success of standardization depends on the use of visual management, which will allow employees to have easy access to production stages, tools and parts needed for manufacturing a given product or providing different services. Knowledge acquired from the entire supply chain allows acting on the flow.

The 3rd principle lies in establishing a continuous flow which is the rate at which resources necessary for the transformation of products and services are allocated. This task involves working continuously with no dawdling, interruption, or rejection, either within or between the steps of the process. Therefore, it is worth studying, designing, and adapting an organization's layout, i.e., the physical arrangement of resources in each workspace, through which an organized production space is made useful by the 5S and visual management.

To achieve a continuous flow, knowledge and application of tools such as cellular manufacturing, production leveling (*heijunka*) and line balancing are relevant towards seeking an ideal flow, i.e., a continuous flow, a single-piece flow or a one-piece flow. In a one-piece flow, instead of manufacturing many products that will then be queued and remain idle for the next stage of the process, products go through each stage one at a time, with no interruptions, thus leading to quality improvement and cost reduction. This flow is considered the opposite of batch production, where parts are processed and moved on to the next process (regardless of need) in which they remain idle for some time.

A continuous flow allows identifying problems that may be an obstacle to an effective transportation of products and provision of services. Thus, there are possibilities for achieving process improvements based on the use of tools of total quality management, total productive maintenance, simultaneous engineering, fast tool change - FTC (SMED - single minute exchange of die), among others.

The evolution of results obtained with respect to items of equipment must be monitored according to the lead time of activities that add value and those that do not, quality rate indicators, performance rate (also called efficiency rate) and defect rates for calculating overall equipment effectiveness - OEE.

Pull production, which is the 4th principle, essentially means that a process should only produce a product, which can be either a good or service, if the previous process had demanded it. When pulling the product, the customer appreciates the delivery of something desired at a given moment of need, instead of what occurs when the supplier attempts to give the customer a hard sell. Womack and Jones (2007) state that the best way to understand the logic and challenge of pull systems is to start from an actual customer expressing demand for a real product and move on to the opposite direction, i.e., by taking all steps necessary to deliver the product to the customer. Details about pull production systems are presented throughout the chapter.

According to lean thinking, perfection, i.e., the 5th principle, occurs when a process provides sheer value (defined by the customer) with no waste. Although this is an ideal scenario by performing a continuous improvement of the system, perfection must be considered goal to be achieved.

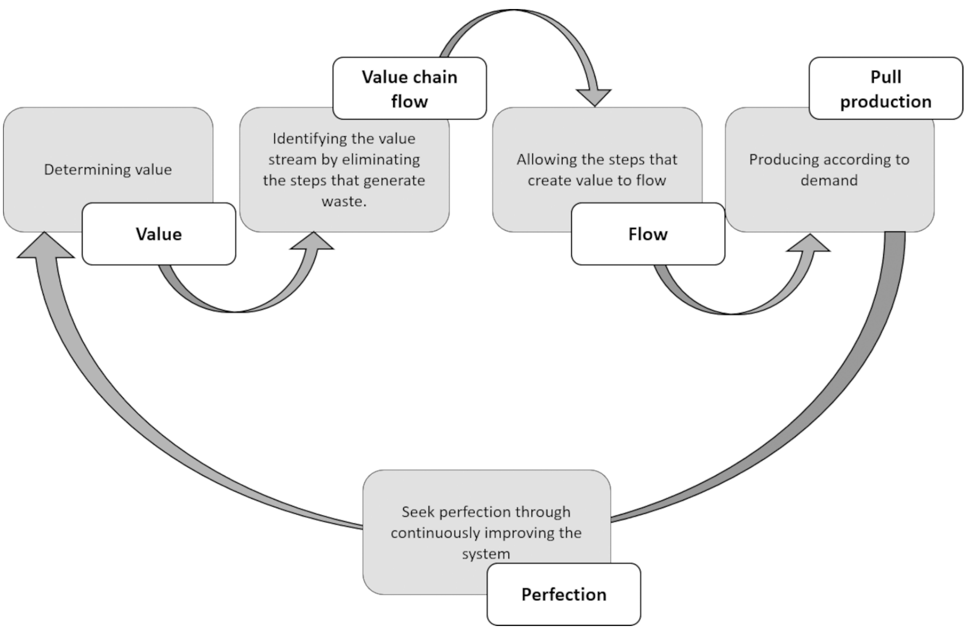
To eliminate waste and seek perfection, companies must make a radical improvement, otherwise known as *kaikaku*, *kaizen* breakthrough, flow *kaizen*, *kaizen* intervention, and continuous improvement, i.e., kaizen, point kaizen and process *kaizen*. *Kaikaku* consists in drastic improvements, usually involving an administrative process that affects the value chain flow afterwards. Kaizen, literally translated as “radical change”, in turn refers to a weeklong, rapidly developing event that adopts a focused, teamwork-based approach encompassing a small gradual improvement of an activity aimed to generate greater value with less waste.

Finally, a constant search for perfection based on concepts of continuous and systemic improvement of processes is based on the use of 5S and *poka yoke*. The latter is defined as a mistake proofing device or procedure that prevents a defect from proceeding to the next stage of operation or process. Audible or visual alarms are examples of poka yoke; or something that enables to halt the process to avoid making mistakes such as: component failure in assembly, part assembled in the wrong position, among others.

By constantly monitoring processes through statistical control and diagnosing the need for changes that allow minimizing mistakes made by employees through autonomation (*jidoka*), which uses automated machinery instead of human intelligence, machines can detect the manufacture of any defective part and can immediately stop performing activities autonomously while indicating the need for maintenance. To systematize these improvements, procedures are used through kaizen projects and the PDCA cycle (plan-do-check-action).

Figure 2 summarizes lean principles as well as their interactions. By applying the first four principles, i.e., value, value chain, continuous flow and pull production, to a system and their interaction, there is the formation of a virtuous circle that provides participants with the view that waste reduction is countless. Such view and application results foster the fifth principle, perfection, which in turn provides a growing increase in the perception of value by customers.

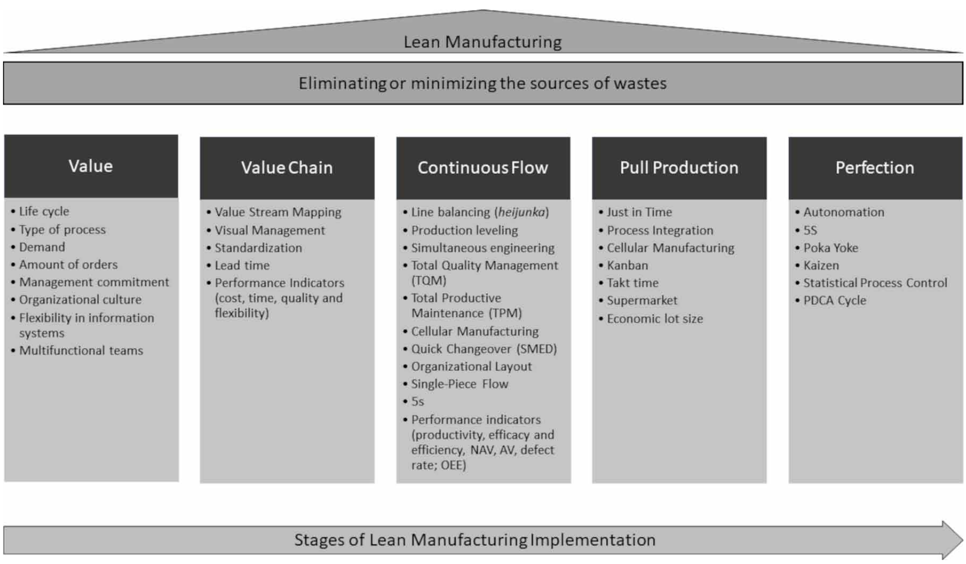
Figure 2. Lean manufacturing Principles



Management based on the elimination of losses and waste proposed by Lean Manufacturing plays an important role, mainly in assisting to mitigate the effects inherent to the particularities of each production system. Lean Manufacturing is implemented in organizations through a coordinated and structured use of several tools, which aids the process of minimizing and/or eliminating waste and inefficiencies from the process, and enables reduced lead time and costs, quality improvement, increased productivity, reliability, and flexibility. In addition, its implementation allows organizations to become more agile, flexible, and innovative, i.e., if achieved successfully.

For the implementation of Lean Manufacturing, a set of tools are used which requires studies that meet the organization requirements. These studies must consider available resources that satisfy and fulfill the organization's objectives. In this sense, the tool *hoshin kanri* stands out, which consists in setting goals and guidelines through a directed effort and established goals to avoid its wrong definition, thus obtaining unsatisfactory results from lean manufacturing implementation into an organization. *Hoshin kanri* is a strategic tool that assists business executives in decision-making processes that focus their resources on critical initiatives required to fulfill the company's business objectives.

Figure 3. Lean Manufacturing, its principles, and tools



THEORETICAL BACKGROUND

Value and Waste (Muda, Mura, and Muri)

The elimination of waste, which means *muda* in Japanese, and the creation of value represent the quintessence of the Lean Manufacturing philosophy. According to Womack and Jones (2007), the underlying issue of Lean Manufacturing involves a way to do more and more with less and less - less human effort, less equipment, less time, and less space - while becoming closer and closer to providing customers with exactly what they want.

Muda comprises a classification called 3MU's used to identify waste. The 3MU's is an acronym for the words *muda*, *mura*, and *muri*. As aforementioned, changes mean waste. Muri involves purposelessness by subjecting employees or equipment to functions beyond their limits (capability). Its consequences are problems regarding safety and quality, interruptions, and defects.

Mura can be conceptualized as inconsistency due to involving production volume fluctuations or irregular production. It refers to subjecting an equipment or employee to functions beyond their capacity at times and below their capacity at others. Such unevenness can be caused, for example, by the occurrence of failures or absence of parts. Table 1 presents a practical example of *muda, mura* and muri.

Table 1. Muda, mura and muri

A worker on an assembly line must manufacture 60 products using a machine that allows working on 20 products simultaneously. ***Muda*:** assembling the products in groups of 10 (6 different cycles). ***Mura*:** assembling the products in 2 groups of 20 cycles and 2 groups of 10 cycles. ***Muri*:** asking the employee to finish production in 30 groups of 2 cycles (condition in which work capacity limits are determined for employees). **Ideal situation:** dividing the products into 3 groups of 20 cycles (a balance between capacity and workload becomes the goal to be achieved).

In most operations, the ratio of value to *muda* is 5/95. Most activities only increase costs and add no value, which makes it crucial to define waste in production processes. Seven types of *mudas* were identified, namely: defects, overproduction, transportation, waiting, inventory, motion and overprocessing. Recently, non-utilized talent was added as the eighth type of waste. Table 2 describes waste in industrial and hospital environments.

Table 2. The seven types of waste

Waste	Hospital environment	Industrial environment
Defects (Errors)	Time spent performing, inspecting, or repairing something containing errors. Example: lack of item in surgical cart or incorrect medication administration.	Manufacture of defective parts or those requiring correction, rework, disposal, or inspection.
Overproduction	Do more than the demand or produce before demand arises. E.g., performing unnecessary diagnostic procedures.	Production of items that are not in demand, which generates transportation costs and losses due to excessive personnel or inventory.
Transportation	Unnecessary movement of "products" (patients, samples, materials) in a system.	Inventory movement (of process and finished products) over long distances which leads to inefficient transportation.
Waiting	Waiting for work activity. E.g., personnel waiting due to unbalanced workload and patients waiting for examination.	Idle time. E.g., employees watching equipment operation, and waiting for work or resources.
Inventory	Excess inventory involving financial costs, storage and transport costs, waste, and damage. E.g., expired medications.	Excess of raw material, in-process stock, or finished products.
Motion	Unnecessary motion of employees in the production system. E.g., employees in each sector traveling long distances due to layout problems.	Useless movement made during work. E.g., searching for parts.
Over processing	Perform worthless work or one which does not meet the needs of the customer. E.g., insertion of data in forms that are not used.	Unnecessary steps to process parts, generating obsolete or damaged products, increased lead times, and incurring transport and storage costs.
Non-utilized talent	Ignored opinions, skills, improvement, and opportunities. E.g., disregarding the opinions of users of the system as a possibility of improvement.	Ignoring proposals for improvements by machine operators.

LINK BETWEEN LEAN MANUFACTURING AND PPC

As described above, the lean philosophy and its tools are successfully used in organizations from different sectors and aid to improve the manufacture of goods and services. When implemented in a production environment, it focuses on improving projects, processes, and products.

Production planning & control (PPC) is aimed at managing the flow of information and materials by focusing on how they go through the production process, but not on process design.

Thus, the PPC determines timing, quantity, and route of production items, while Lean Manufacturing improves these environments through continuous improvements that bring benefits to different levels of PPC.

The demand forecast established by PPC is positively affected by Lean Manufacturing which aids to reduce preparation time. It does not directly affect the development of production plans, since these are still necessary, but it reduces the complexity of the master production schedule (MPS) by allowing its elaboration time to be close or the same as that of the rate of sales.

In production planning, establishing a partnership relationship with suppliers allows the purchase process to be reorganized towards reducing lead time in the supply chain, thus favoring the creation of a synergistic work environment that promotes an organized and continuous flow of materials.

Lean Manufacturing implementation positively affects the master production schedule (MPS) by making delivery times shorter. The closer the time to manufacture a given product is to estimated delivery time calculated by the sales team, the less is the need for forecasting and, therefore, the planning horizon. The tools of lean manufacturing enable a stabilization of production processes by allowing the use of just in time (JIT), which assists in manufacturing items to meet customer demands only at a moment in which they place an order.

As regard material requirements planning (MRP), Lean Manufacturing aids to reduce inventories (raw material in the process and finished products), since a reduction in lead time allows products to be manufactured according to the customer's need to follow the customer's order as close as possible to its request date and run the production flow continuously. A reorganization of production environments by adjusting the layout and cellular manufacturing reduces the number of products to be assembled and, consequently, their component lists, thus facilitating management and determining production sequencing.

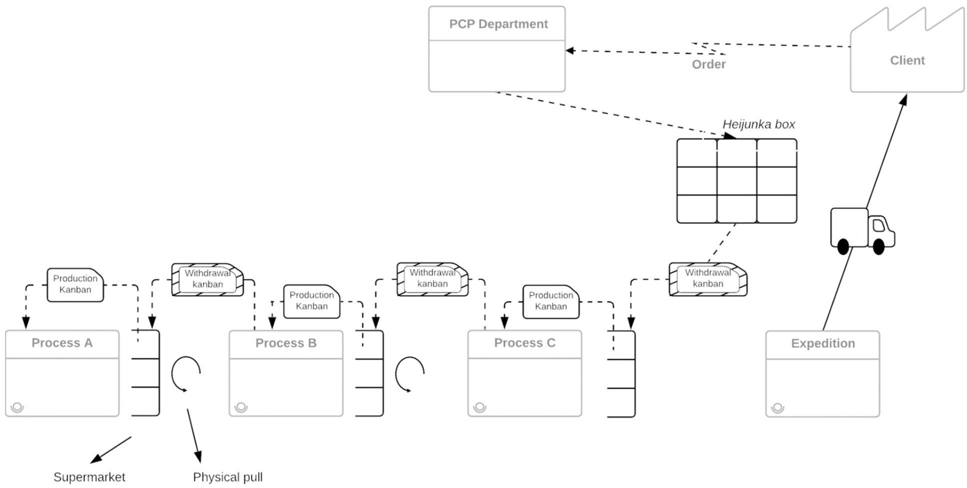
It can be observed that PPC is necessary in a lean environment, just as PPC environments require Lean Manufacturing practices if they are willing to improve competitiveness and become more effective and efficient.

PULL PRODUCTION SYSTEMS

The central principle of pull production is that there must be a continuous optimization along the value-adding chain oriented towards customer demand. This effort is aimed at increasing customer satisfaction, in which the waste of inventory is avoided, and simple and transparent processes are generated. Thus, companies are posed with the challenge of making the right product available at the time, on the spot, in quantities and at a level of quality desired by the customer, and at minimum cost.

A production system oriented towards pull production is described in literature in three different ways: supermarket pull system, sequential pull system and mixed pull system (sequential with supermarket).

Figure 4. Schematic of a supermarket pull system



Supermarket Pull System

In this type of pull production system, the term used in its name, supermarket, is used as basis for its operation.

A supermarket represents a place where customers buy items. It has inventory control (also called a buffer) used to set up an upstream process. In such supermarkets, minimum and maximum amounts of raw materials, items and assembly groups are maintained to meet the demand of subsequent processes. At supermarkets, the customer or the next process removes the necessary items from shelves, which triggers the replenishment of items by the seller, i.e., the previous process.

Inventory control in supermarkets (minimum and maximum quantities of items and production flow) is managed with the aid of *kanban* cards which is made possible by the *heijunka* box through visual management to allow a practical and easy inventory replenishment control. The *kanban* card is normally placed in a rectangular vinyl envelope that allows visual controls and management of the flow of information to regulate the supply of materials between processes. The *heijunka* box is a visual programming tool used to promote production leveling aimed to allow a smooth flow of items production. Its appearance can be, for example, that of a rectangular cube, divided into boxes (box) that represent a given time to produce a certain set of items. At the top of the box, there is a schedule in specific time units that provides the current stage of production.

The production of new items takes place by inserting *kanbans* that are added to the *heijunka* box, thus providing a visual representation of the following items to be produced. The *heijuinka* box allows operators to easily visualize the following tasks in a production process, in addition to the time at which they are scheduled for. Visually, the concept of supermarket pull system, otherwise known as replenishment, pull system, is outlined in Figure 4.

From the moment that there is the need for producing a particular item according to the *heijunka* box, the withdrawal *kanban* is collected, which establishes the need for process C production. Process C checks the availability of items and starts their production. Depending on the need for production, process C removes items from the supermarket provided by process B. Once it is noticed that there are items requiring replenishment established by the supermarket (determined by *kanban* tags assignment), process B starts manufacturing them as needed, and the items made available by process A are removed from the supermarket for product manufacturing. Thus, each process is due to keeping its supermarket stocked with items it produces. This type of pull system is effective for companies that have a small variety of items.

Sequential Pull System

The sequential pull system differs from the previous one in such a way that it is recommended for an organization in which there is a wide variety of items. When selected, the storage of all types of items in supermarkets is not feasible.

As a solution, it is recommended to change the production environment into order placement which minimizes total inventory.

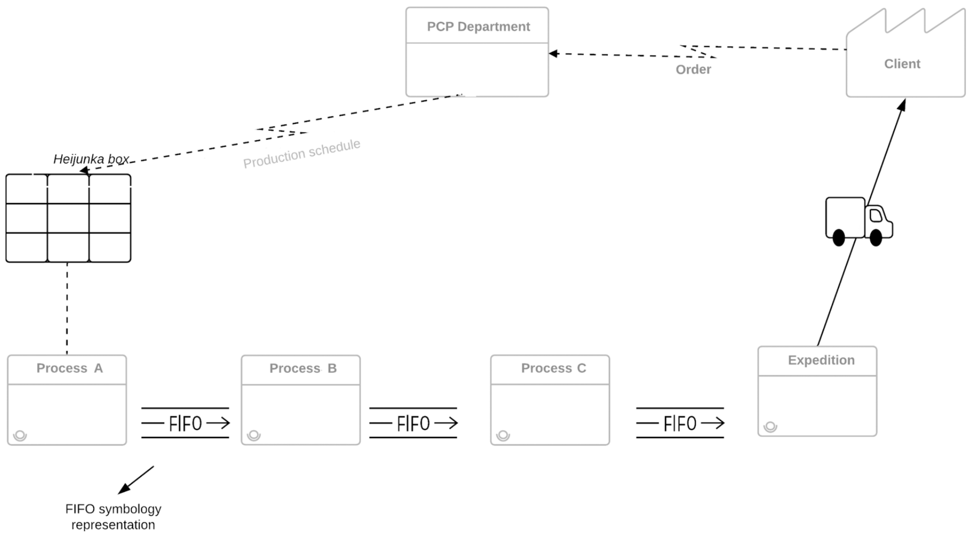
Therefore, the role of the PPC department becomes fundamental to determine the production mix and the quantity of items to be produced.

Commonly, for such cases, sequencing is guided by the concept of first in, first out - FIFO. In this type of sequencing, the objective is to respect the order in which orders are placed with items that arrive at each process being produced based on what was originally defined in the sequencing and presented by the *heijunka* box.

For a sequential pull system to operate properly, there is a need to be aware of the lead time of items, and that such lead time in the supply chain is the same between processes, or that there is already an adequate and minimum inventory at the supermarket to avoid the wastes of overproduction, inventory or waiting.

Figure 5 shows a sequential pull production system which, based on the customer's request, the PPC Department determines the production schedule to meet the customers' needs and have the best production mix for the factory floor, which is made available by means of the *heijunka* box. Once schedule is defined, Process A starts manufacturing items which are made available sequentially to process B until the final product manufacture occurs, which is then sent within the estimated delivery date.

Figure 5. Schematic of a sequential pull system



Mixed Pull System (Supermarket Sequential Pull System)

The third type is called mixed pull system, as it operates based on the concepts presented in the two previous models, i.e., the supermarket and sequential pull systems. This type of pulled system is recommended when there is a variety of items, although it is noteworthy that few items represent a large production volume.

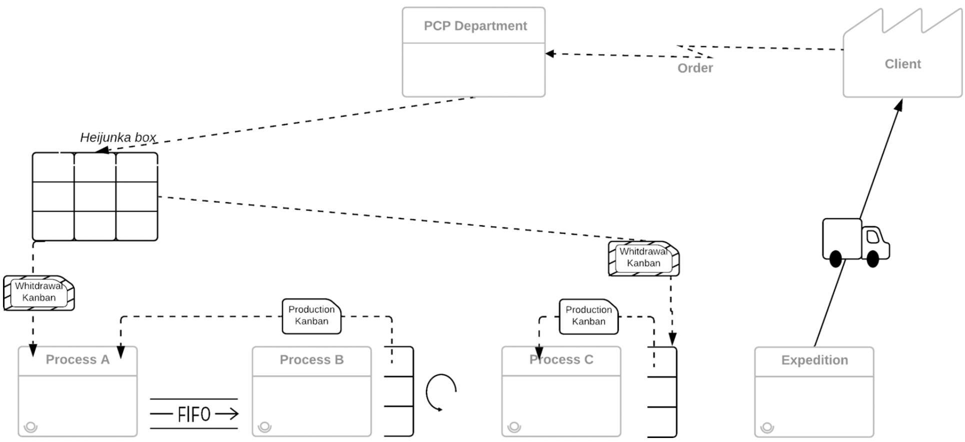
For identifying these representative items, the ABC classification concept is used to determine 20% of A items (called high ordering rate) that represent 80% of the production volume. Items B are classified as average ordering rate and items C as low ordering rate.

Items A and B are commonly managed by the supermarket pull system due to the rate of orders and constant production. Less frequent items, such as C items or even special requests are inserted into the supply chain schedule using the sequential pull system, as pointed out by the PPC Department.

The complexity in managing the two pull system models requires extra care in assigning daily activities in the mixed pull system to identify potential improvements and waste in production processes.

It can be seen in Figure 6 that after receiving an order by the PPC department and the classification of the requested item, a supply chain schedule is established and taken to the *heijunka* box. Items A and B are removed at appropriate time by process C, which starts manufacturing the item from those available in process B at the supermarket. When it is identified that the items supplied require replenishment, their production begins by withdrawal *kanban* from the production in process A, which directs production to process B and follows the sequencing. For orders classified as C items, production is sent to the *heijunka* box and, at the time set for production, it is initiated by process A to run smoothly through the other production stages.

Figure 6. Schematic of a mixed pull system



Pull Production and PPC

Lean Manufacturing is the origin of the concept of pull production, which is a primary aspect of JIT and an alternative to the concept of push production defined by PPC.

In push production, items are produced to meet future demand estimated by forecasting models or created through marketing actions. Thus, items are produced in their final state, or at least close to it.

In pull production, manufacturing orders are issued when there is a real demand, which generates lower intermediate and final product inventory to avoid the waste of overproduction. For such a purpose, the use of small manufacturing batches and production leveling recommended by Lean Manufacturing aids to avoid that organizational performance is adversely affected by changes in orders, problems with suppliers, forecast errors and product defects.

The role of PPC in productive environments in which pull production has been implemented is relevant, mainly for sequencing orders of customers and controlling inventory during production stages.

When the supermarket pull production system is adopted in a production environment, PPC is responsible for informing the needs of the final consumer, which triggers the entire pulling process along the production line. In a sequential pull production environment, the role of PPC is to establish the most effective order for production by considering the characteristics of each workstation and making it available on the *heijunka* board. Finally, in a mixed production system environment, the PPC identifies the complexity of managing the characteristics of the two previous types.

JIT Model/Kanban Method

The pull production system is an effective way of JIT production and it efficaciously promotes the level of production and operation management of companies. JIT production conceptualizes the need to produce the necessary product at the right time, in the right quantity and thus eliminating unnecessary inventory.

The JIT model is a production planning approach that replaces material requirement planning for better materials management because it works on the principle of zero inventories. It inflicts highly enforced quality control processes to ensure that the product meets quality specification as per customer requirements. It is a pull system of operation, in which the point of application of a worker represents the actions of others (Kaswan et al., 2019).

The *kanban* method was developed for pull production aimed to manage JIT production.

The term *kanban* means signboard and is currently used in manual or automated forms such as electronic *kanbans*. It allows a visible and harmonious control of production and inventory quantities in a production system. The replenishment of stocks on supermarket shelves represents the basis of the *kanban*.

The use of *kanban* enables to level production and obtain a reduction in the stock of finished products and raw materials and, consequently, lead time. Constant changes in orders by customers are no longer a problem, as the company's production can adjust the pace of items to be produced during the day, week, or month. In addition, there is an increased flexibility of response to customers, which results in a production which is closer to the actual demand.

The *kanban* plays an important role in communicating information throughout the product's production cycle and ensures manufacture of the right number of items needed at the right time. Such information communication is carried out through two basic types of *kanban*: withdrawal and production, as shown in Table 3.

Kanban cards, as a means of visual management of production control, employ three colored tags, which are green, yellow, and red, that allow the employee to identify whether items need to be replenished or not.

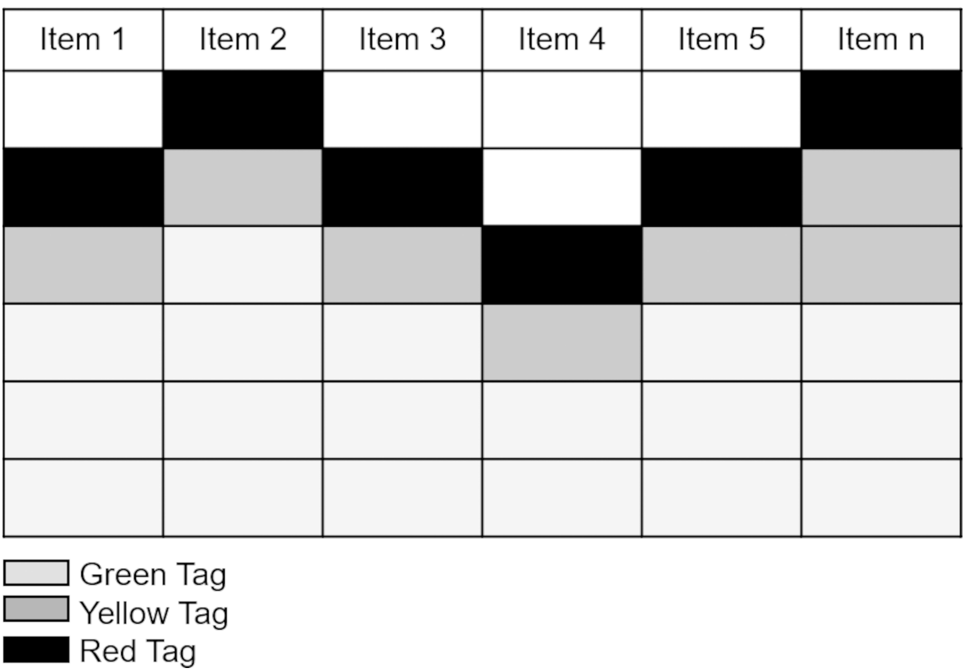
The green tag defines production leveling. At that time, there is no need for production. The yellow tag sets response time. While using items of the green tag, and entering the stage of the yellow tag, it is necessary to produce the item. Then, the due production process must finish its production, carry out its setup, produce a transfer batch and place it on the supermarket shelves. Finally, the red tag represents the necessary safety so that there is no halt in production at sectors, and it exists to safeguard production from any problems in the supply chain process.

Table 3. Types of kanban and their definitions

Types of *kanban*	**Other nomenclatures**	**Definition**
Withdrawal *kanban*	Move cards Conveyance Kanban	It authorizes to move products towards a downstream process (customer). This card must contain information on the type and quantity of product to be moved.
Production *kanban*	Manufacturing Kanban	It authorizes the manufacture or assembly of items in downstream processes (customer) based on the use of upstream processes (supplier).

The tags are determined according to the needs to replenish each item. Thus, there are variations in the number of kanbans, as shown in Figure 7.

Figure 7. Schematic of kanban and its colored tags



To Kanban function correctly, it is recommended to follow four rules: (1) the customer should only take items from the stock when it is in fact necessary; (2) the supplier can only produce items which have production *kanbans* and in quantities defined therein; (3) only good parts can be placed in stock; (4) *kanbans* must be in full packages or on a signboard.

Determining the Number of *Kanbans*

The number of *kanbans* is calculated using the following equation.

$$N = \frac{UxT\left(1+P\right)}{C}$$

Where:

N = total number of containers needed between the two workstations (i.e., number of *kanbans*)

U = utilization rate of the next workstation, usually measured in items produced per hour

T = average elapsed time required so that the container completes the entire cycle from the moment it leaves the previous workstation, and it is filled with products and leaves again.

P = policy variable that indicates the efficiency of the system. P can have values from 0 to 1, where 0 indicates perfect efficiency and 1.0 indicates total inefficiency.

C= Standard container capacity in terms of number of items.

For instance, let us consider an auto parts industry which operates 24 hours a day and has a wide variety of parts to meet different customer requirements, and that each customer has different demands for these products. The company adopts the pull production system, and its production is daily. However, when necessary, the push system is used for products having less demand.

For one of the company's production lines, customer demand for a period of fourteen days is known, which is shown in Table 4.

Table 4. Customer demand for five types of products

Period	Parts				
	A	B	C	D	E
1st Day	4.890	1.360	1.870	1.310	1.100
2nd Day	4.890	1.360	1.870	1.310	1.350
3rd Day	4.890	1.360	2.540	2.260	840
4th Day	4.890	0	1.870	0	0
5th Day	4.890	2.720	1.870	0	0
6th Day	0	0	0	0	0
7th Day	0	2.720	1.920	0	840
8th Day	4.890	1.360	0	0	0
9th Day	4.890	1.360	2.540	1.310	1.230
10th Day	4.890	1.360	1.870	1.310	840
11th Day	4.890	1.360	2.520	1.310	1.470
12th Day	4.890	1.360	2.540	1.310	840
13th Day	0	0	1.870	1.310	700
14th Day	0	1.360	720	0	450

Table 5. Production mix planning for the five types of products

Period	Parts				
	A	B	C	D	E
1st Day	3.750	1.370	1.970	800	750
2nd Day	3.750	1.370	1.970	800	750
3rd Day	3.750	1.370	1.970	800	750
4th Day	3.750	1.370	1.970	800	750
5th Day	3.750	1.370	1.970	800	750
6th Day	3.750	1.370	1.970	800	750
7th Day	3.750	1.370	1.970	800	750
8th Day	3.750	1.370	1.970	800	750
9th Day	3.750	1.370	1.970	800	750
10th Day	3.750	1.370	1.970	800	750
11th Day	3.750	1.370	1.970	800	750
12th Day	3.750	1.370	1.970	800	750
13th Day	3.750	1.370	1.970	800	750
14th Day	3.750	1.370	1.970	800	750

Table 6. Number of kanbans for each type of part

Item	U	T	P	C	K
A	3.750	1.020	0,30	450	8
B	1.370	1.020	0,30	150	9
C	1.970	1.020	0,30	230	8
D	800	1.020	0,30	40	19
E	750	1.020	0,30	150	5

The PPC Department carries out the process of determining the production mix according to the forecast of customer demand according to Table 5. These data represent the utilization rate (U) of each part daily.

The next step is to calculate the average elapsed time required for the product to complete the entire cycle (T), which is the result of a sum of *kanban* collection time (T1), waiting time (T2), replenishment time (T3), processing time (T4) and shipping time (T5).

$$\mathrm{T} = \Sigma\left(T_1 + T_2 + T_3 + T_4 + T_5\right)$$

For the case under study, the time for the *kanban* to be sent from the supermarket to the production line is 50 minutes (T1 = 50 minutes). Waiting time (T2) for production is 830 minutes. Replenishment time (T3) is 25 minutes, processing time (T4) is 25 minutes and shipping time (T5) from the supermarket to the warehouse is 90 minutes. Thus, the production cycle time (T) is:

$$T = 50 + 830 + 25 + 25 + 90 = 1.020\left(min\right)$$

Let us suppose that, for part A, the system efficiency is 0.30 and the capacity of a standard container is 450 items. The *kanban* quantity is then calculated as:

$$N_{(Items\ A)} = \frac{UxT\left(1+P\right)}{C} = \frac{\dfrac{3.750\,pç}{24h\,x\,60\dfrac{min}{h}}\,x1.020min\,x\left(1,30\right)}{450\,pç} = 7,67 \therefore 8\,kanbans$$

The method of calculating *kanban* production for the other items is similar and the results of calculating the *kanban* quantity of these five types of products are shown in Table 6.

Therefore, the number of *kanbans* for the entire production line has already been calculated. The PPC Department prepares and releases the *kanban* based on the calculation result, and the production department schedules production according to information provided by the *kanban*.

Determination of Tags

The calculation of the number of *kanbans* (N) ensures that the production system will have enough items in stock at the supermarket to meet its daily production. In this case, the calculated N value makes it possible to establish green and yellow tags.

Taking the previous case as an example, a set of 8 *kanbans* is required for item A, i.e. 8 containers with 450 items each, which will meet the demand of 3,750 items to be utilized daily. It is now necessary to identify the moment at which the previous process needs to start producing items to replenish the containers that will be used along the day.

To determine replenishment time, which represents the yellow tag, it is necessary to identify (TF1) average time to finish producing items in the process; (TF2) average time to prepare machinery for producing the item; (TF3) time to produce items of a container; and (TF4) time to ship the container to the supermarket in the supply chain process.

If the supply chain process for A items lasts as follows:

TF1 - average time to finish producing items in process - 45 minutes.
TF2 - average time to prepare machinery for producing the item - 15 minutes.
TF3 - time to produce A items of a container - 250 minutes.
TF4 - time to ship the container to the supermarket - 10 minutes.

The sum of these values amounts to 320 minutes required for the supplier to replenish a container at the supermarket. Assuming that there is a demand for 3,750 items to be used over the course of a working day, the utilization rate is 2.6 items per minute.

Thus, if the production of 1 container requires 320 min, 832 units of A items (320 min x 2.6 items/min) will be utilized over that period, which indicates that 02 containers are required according to the yellow tag. Given the need for 8 *kanbans* for item A, it results in the green tag, representing 06 containers.

The red tag considers average repair time in case of machinery stoppage or in the absence of products due to failures by the supplier associated with safety stock.

Table 7. Calculation of kanban tags adjusted according to type of items

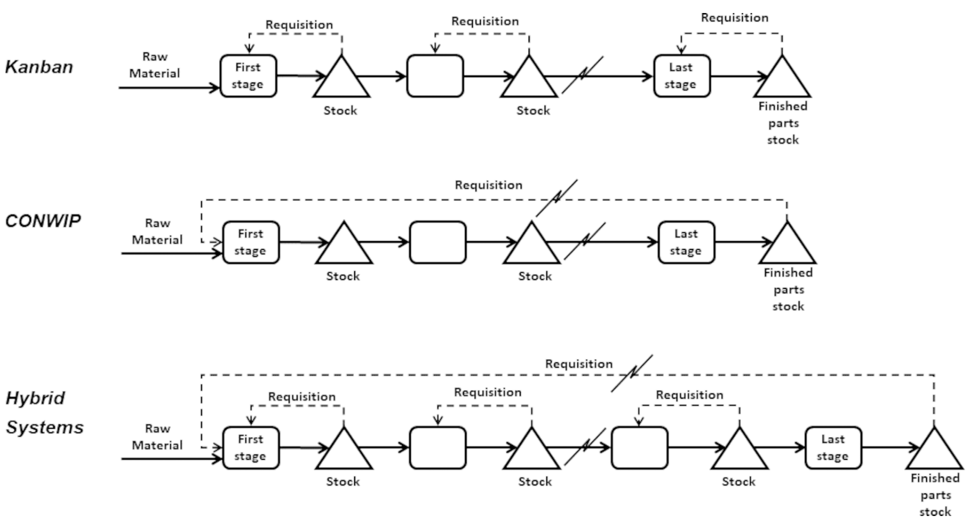
Item	TF1	TF2	TF3	TF4	Maintenance Time (hour/ day)	Consumption rate (items/min)	Green *Kanban*	Yellow *Kanban*	Red *Kanban*
A	45	15	250	10	1	2,60	6	2	1
B	45	15	210	10	1	0,95	7	2	1
C	45	15	90	10	1	1,37	7	1	1
D	45	15	220	10	1	0,56	15	4	1
E	45	15	120	10	1	0,52	4	1	1

If item A were supplied internally and the average time to repair defects in machinery were 1 hour a day in the supply chain process, 156 units of A items (2.6 items/min x 60 minutes) would be utilized in this period. If each container holds 450 units, there is a need for 1 container in the red tag, i.e., 1 *kanban* in the red tag.

Thus, the number of *kanbans* adjusted for the total A items is 9:8 (*kanban* to meet daily production), being 6 *kanban* green tags and 2 *kanban* yellow tags, and 1 *kanban* red tag.

For the other items, the calculation is similar, as shown in Table 7.

Figure 8. Kanban, CONWIP and Hybrid Systems



Hybrid Production Systems

CONWIP - constant work in process - is a pull system as a generalized form of *kanban* as it depends on signals. However, in the *kanban* system, each card is used to indicate the production of a specific item, but these cards are assigned to a cycle that covers the entire production chain and does not correspond to a specific item in CONWIP. The specific need for an item is represented by cards at the beginning of the production chain, e.g., it is determined according to a log of demanded items called as backlog. When it is necessary to start production, a card is removed from the production chain and marked as the first type of item on the list to be produced for which raw material or components are present in a standard container at the beginning of the production chain.

The CONWIP illustrated in Figure 8 is applicable to production environments that manufacture different types of products. The CONWIP system seeks to control the plant at a constant level of work in progress, although it does not attempt to control the location of the WIP within the system.

To identify whether a production line behaves as a CONWIP system or not, the following parameters are observed: a) number of signboards (to determine the maximum level of WIP); b) target production quota (for a given period); c) the maximum amount of work ahead. If the target production quota were added to the maximum amount of work performed during a given period, the line would come to a halt until the beginning of the next period; d) a trigger of lack of capacity as a function of effective production until a given time. By satisfying these parameters, it is possible to consistently adjust the production system to the CONWIP method, thereby avoiding non-compliance with the benefit proposed by the method.

CONWIP is like technique used in air traffic control. On days of heavy air traffic, a departure plane will sometimes be kept on the ground at the airport of origin, instead of being allowed to take off and remain in a waiting pattern at the congested destination airport. As the objective is to avoid delays at the destination airport, planes are kept in the air, even if runways are free at the airport of origin, therefore increasing safety and reducing fuel consumption without additional delays.

In this example of CONWIP application in air traffic control, a job will not start unless a location in the system has been vacated for it. The same balancing challenge that air traffic controllers face must be met in CONWIP. Excess work, such as airplanes in the air, must be placed on the ground while arriving so that the bottleneck station, which is the runway, is seldom idle, but not for the point of work, i.e., airplanes, having to wait for too long. If successful, the system will achieve a maximum throughput without excessive flow time or WIP. CONWIP will naturally follow what had been stated by Goldratt (1984), in the book "The Goal", which aimed to balance flow, not capacity. The operation of a CONWIP line is regulated according to bottleneck features.

Integration of MRP, *Kanban* and the Theory of Constraints

By constantly seeking optimizing customer service and reducing costs and inventories, systems such as MRP, *kanban* and the theory of constraints (TOC) stand out, however, to reap better benefits, one must focus on the production strategy inserted in the context of a business environment, as described in Table 8.

MRP, also known as ERP, is a forecasting system that provides answers related to deadlines for making, buying and assembling components at all levels of product structuring. It depends on reliable data from the company's infrastructure to ensure good decision making. Operations and service environments are dynamic and constantly changing, which leads to less efficiency and high costs in the case of incorrect data.

The just in time production approach and *kanban* are alternatives to simplify the see and act in a quick reaction system. Kanban assists in lead time reduction and might eliminate or reduce uncertainties in process and inventory, thus making production efficient, although it depends on a stable and predictable environment. The *kanban* system is favored by a level production with predictable demands and few processing problems, such as long setup times, low equipment availability, few product changes, and a good level of reliability of suppliers' deliveries.

Table 8. Peculiarities of Systems

System	Advantage	Disadvantage
MRP (ERP)	Resource forecasting instrument.	It depends on the reliability of data to generate assertive information.
Kanban	Simplifying the information system and corroborating to reduce lead time.	Low compliance with an uncontrolled environment involving high setups and low availability of equipment in an unpredictable and volatile environment.
Theory of constraints	Identification and improvement of bottlenecks in the operation.	Low efficiency in a product mix environment followed by very often changes in the constraint during a given day.
CONWIP	Applicable to environments with a wide variety of product types.	Stock levels within the system are not individually controlled.

The theory of constraints – TOC, is a similar system to the Kanban method in which it is adopted a principle establishing that difficulties are related to a factor called *constraint*. When the bottleneck is identified and managed, for example minimizing high setup time the bottleneck equipment which is a constraint in an operations environment, benefits are generated to process management, given that there is no significant modification in the product mix followed by changes in the constraint along the day.

Production planning using the drum-buffer-rope (DBR) tool aims to synchronize production by balancing the production flow, and not the individual capacity of each process, which is one of the tools of the TOC. The drum-lung-string tool was created based on the five TOC focusing steps, which are: 1. Identifying the system constraint; 2. Exploiting the system constraint; 3. Subordinating the entire production system to its constraint; 4. Elevating the system constraint; 5. Restarting: after action is taken, in which the constraint should still be the focus of attention, unless it is no longer a constraint.

In specific cases, hybrid systems are alternatives to improve the results of operations, such as when you have a conventional production system, and you wish to start turning it into a lean system. Rother and Shook (2003) utilizes value stream mapping to illustrate a push system by using MRP in the production system, which evolves to the *kanban* system in the future value stream mapping without MRP in the lean production system, but through a combination of *kanban* and MRP which is also rather common in literature. In a hybrid MRP and *kanban* system, MRP is used for advanced planning and the *kanban* acts as an execution system on account of its characteristics of quick response to customer orders and reduced levels of inventory along the process. In a hybrid system that integrates Lean Production with the TOC, the TOC prioritizes areas for improvement and the principles of lean production, in addition to promoting process improvements from the elimination and/or reduction of waste.

By allowing data on the WIP (work in process) to be collected further up ahead in the process or at the bottleneck, CONWIP can operate with less WIP than *kanban*. CONWIP uses the number of pending items, which can allow task sequencing to be performed by production planning & control personnel. The backlog sequence can be a way to ensure adequate capacity when there are significant configurations and optimize production synchronization of item components.

IMPLEMENTATION

In this section, we present the case of a production system in the sector of pad printing of injected items which is responsible for the manufacturing process of subsets used in a domestic refrigerator. The sector has three macro processes considered as departments: (i) plastic transformation, where the study has been carried out; (ii) metal transformation and (iii) product assembly. In this case, there is an internal customer, which is part of the company's logistics policy, its distribution center structure and external customers who are distributors through their stores, such as Casas Bahia and Magazine Luiza (in Brazil), and the final consumer, i.e., the consumer.

In this manufacturing process, the main indicators for managing safety, quality, production, and costs used in this production system are products per operator, service to the product mix, sales price per hour of direct work, number of employees, amount of overtime, level of consumer satisfaction, indicator of production errors, number of field complaints, number of accidents, cost of refuse and rework, material cost and stock days.

In its initial stage, the sector of pad printing of injected items classifies its production flow as a functional layout. This sector almost always served the customer in terms of production volume, despite constant variations in the product mix. This layout favored the company by partially protecting customer service, even when there was machinery breakdown, long setups, lack of employees and other types of waste. However, areas of improvement were identified, such as: waiting time, disorganization, refuse, stock in process, improper use of resources and non-conformities in terms of safety, ergonomics, and quality.

In view of a consensus on the need to improve the layout of the sector of pad printing injected items, a multifunctional team, trained in the concepts of lean thinking, starts introducing good practices and tools from the pull production system. It was proposed by envisaging a possible elimination of the safety problem, reduction of losses and waste, and an increase in quality and productivity indicators.

To guide the improvement project, short-term goals (6 months) were agreed upon aimed at an enhancement of safety, quality, productivity, and strategic production planning guidelines, which are: to reduce 25% of the stock in process, increase 10% productivity, gain 15% of utilized area, study the possibility of improving production flow, and eliminate the safety problem in rack/corridor movement.

Figure 9. Outline of the current layout

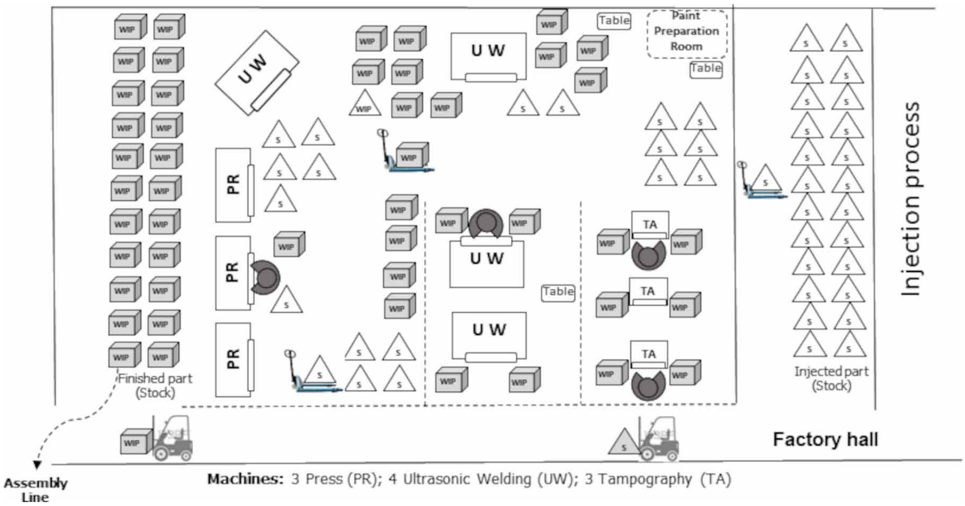
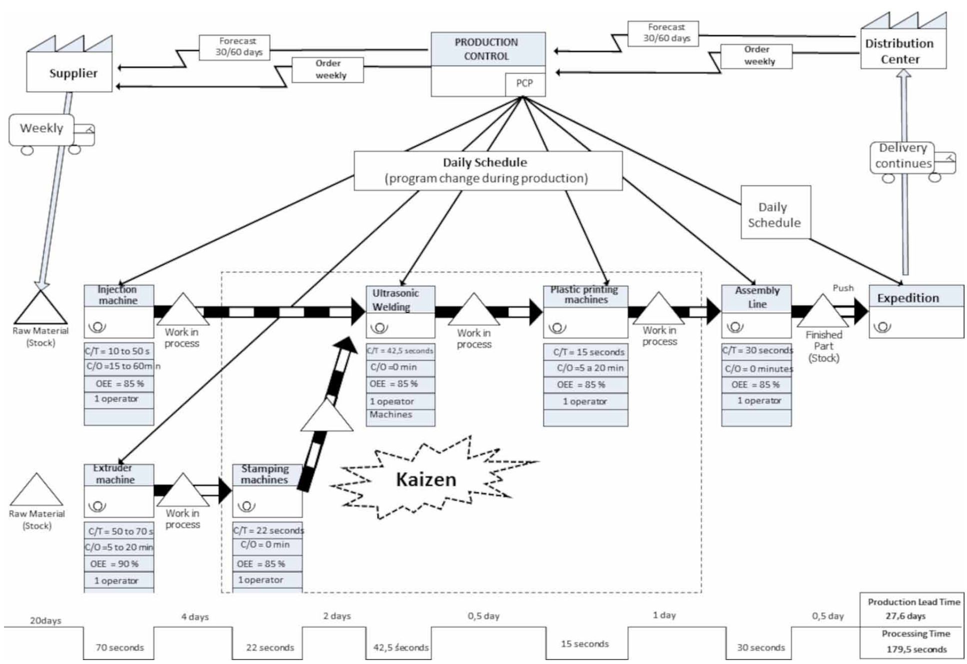


Figure 10. VSM of a Push System involving a refrigerator defrosting tray



Visualizing the Flow of the Sector of Pad Printing of Injected Items

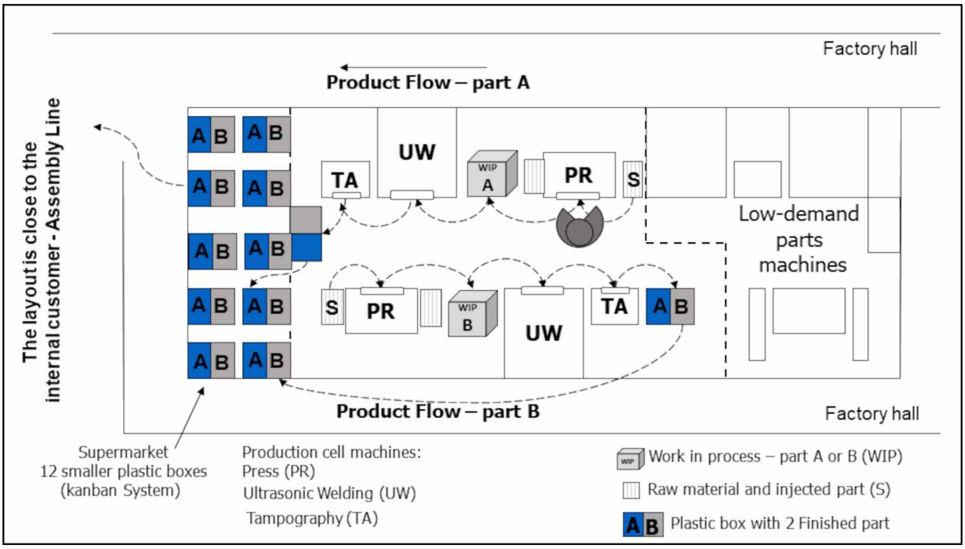
To understand the sector of pad printing of injected items, it was initially measured the area, bench, machinery, and packaging for designing the current layout. An outline of the current layout demonstrates three presses (PR) used for cutting plastic sheet, four ultrasonic welders (UW) used to join plastic parts and three tampography machines (TA) used for pad printing the plastic part, as shown in Figure 9. The stock in process stored in a steel wire rack (WIP) is within the pad printing area, and the stock with several ready-made subsets and parts also utilizes a steel wire rack, which is symbolized by the letter S. There are four operators per shift and a total of nine operators working double shifts by considering a supervisor working during administrative hours. The production sequence of the two families of sub-assemblies studied is: the first process is with a hydraulic press, the second one is with an ultrasound welder, the third one is with a pad printer (tampography machines) and the last one is to send final products to stock. It is worth mentioning that steel wire racks are moved and stored using forklifts, and packages are moved and repositioned with a hydraulic hand pallet truck in the pad printing area. In this case, the flow is not continuous, and work is carried out according to manufacturing orders controlled by the planning and production control - PPC sector.

In this study phase, the multifunctional team started out from understanding that the push production system makes it difficult to meet the company's functional requirements, such as daily changes in the product mix and production volume. It is also observed that stock in process stored in steel wire racks contributes to area misuse. From that point on, the stage of analyzing the initial situation and projecting a future scenario of the sector was carried out through the value stream mapping (VSM) of pad-printed items. For this purpose, the family of products called defrosting tray and evaporator door of domestic refrigerators was selected. The current value stream map is shown in Figure 10.

The VSM of the current process for the evaporator port subset family (A) and the defrosting tray (B) involves a press, ultrasound welders and pad printing machines. Subsequently, the station supplies the automatic assembly line. The pad printing sector depends on the injection machine sector and has a single shared plastic sheet extrusion machine as its internal supplier. It is also observed that there is a high level of inventory before, during and after each process.

As examples, it is mentioned the raw material received at least once a week and stored in a warehouse for 20 days or so depending on deliveries. After the injection and extrusion processes carried out by different and distant departments in the plant, 4 days of stocking manufactured parts have been mapped and allocated to a warehouse of stock in process. In the pad printing sector alone between three different processes containing ten machines, which are three presses, four ultrasound welders and three pad printing machines, 3.5 days of in-process stock have been mapped, i.e., involving parts stored in a steel wire rack and moved several times.

Figure 11. Outline of cell layout of the pad printing process



The assembly lines take 1 day to stock evaporator door subsets (A) and defrosting trays (B), which is why the flow of final product assembly is hardly ever interrupted. Subsequently, while assembling the product, these are sent in batches directly to the logistics distribution center, which in turn equates deliveries to customers and informs demand to the production planning and control department.

Then, the production planning and control sector assumes the role of operator of the push production system through production orders for what to produce, how much and when to proceed to the following process. Through the value stream mapping, production rate, i.e., takt time for manufacturing subsets is defined. The cycle time of the press is 22s, that of the ultrasound welding machine is 42.5s and the pad printing lasts 15s. The sector works double shifts whose work hours equal 8.4h/shift with 15% of the time spent at lunch and other necessary stops. Therefore, the time available is equal to 7.14h/shift or 25.704 s/shift considering a demand for 300 subsets a shift, which results in a takt time of 85s for both subsets.

In this configuration, the PPC department issues the order of production and delivery to those responsible for each sector and/or equipment based on the priority of daily delivery scheduled monthly and reviewed weekly.

FUTURE IMPROVEMENTS TO THE CURRENT PROCESS

The outline of a future layout shown in Figure 11 comprises the change of layout through the creation of a cell composed of three types of equipment added to a supermarket at the end of the process to meet the customer demand level in any circumstance. It has not been demonstrated, but it is worth mentioning that it was necessary to reduce the wired-type packaging by smaller plastic packaging to eliminate the need for a forklift in the cell. There was also a reduction in area and the possibility of accidents ceased to exist, as there has been a layout change from functional to mobile. The cell was designed and installed close to the following process (main assembly line), thus being close to the previous process (extrusion process) and away from the injection process.

Another important factor is overproduction that occurs at the same time as the lack of unscheduled components, but it cannot be stated that only one type of production system is ideal. It depends on several variables, mainly on functional requirements. In the case of this company, specifically in the pad printing sector, the push system was considered one of the causes of waste that does not add value, such as inventory and overproduction.

The cell was designed by considering the flexibility to meet the changes in customer demand without generating high inventory in process and considering the priority of assembly lines. The cell was designed for a collaborator by considering takt time of 85s for the two previously mentioned subsets, however, two or more collaborators must be added to work simultaneously in case of a larger volume.

The finished set packaging has changed from standard steel wire racks to smaller plastic boxes. In each plastic box, the defrosting tray subset and the evaporator door subset were stored in the same proportion. The mixing of different parts in the same packaging occurred due to the point of use in the same final product on the assembly line. Therefore, the packaging was shared by two subsets.

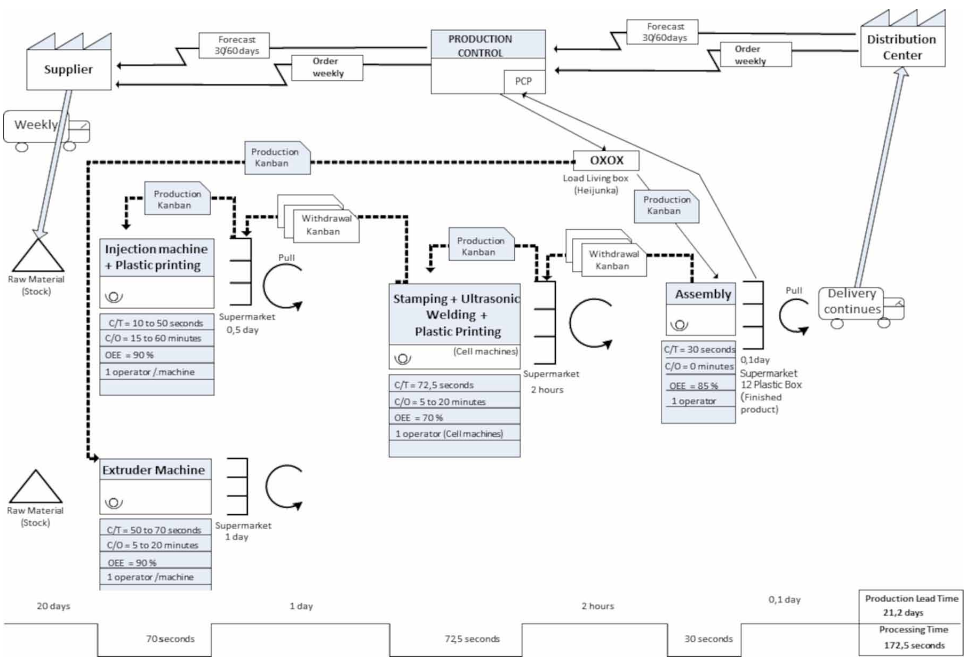
To ensure sales cadence on the assembly line, the operator's routine was standardized in which the method was described in an orderly fashion. Another relevant aspect was the visualization of limits by cycle time versus takt time.

The routine of standardized operations, in addition to establishing the sequence of activities that each employee performs within a given cycle time in a pull system, is relevant to reach the preset takt time and meet customer demand. Such a routine has two purposes: the first one is to provide the operator with a sequence order or routine to pick up the part, place it in the machine and remove it after the process, and the second one is to determine the sequence of operations that a multifunctional employee must perform on multiple machines during a cycle time.

Despite the proposed improvements, such as the establishment of production cells and standardized work, possibilities for future improvements in this cell were envisaged. It is observed that there is a level of utilization of 20% of machines (17s/85s = 20%), and that the operator works 86% of the time and rests 14% of the period. It is also noted that the cell productivity can improve because that the operator travels 30% (25s / 85s = 30%) of time inside the cell and 56% (47.5s / 85s = 56%) of time is spent on handwork. This enables to conduct future studies on the implementation of autonomation.

The study on cell layout and the development of standardization allowed redesigning the company's value stream mapping and establishing its future state, as shown in Figure 12.

Figure 12. VSM of a supermarket pull system



CONCLUSION

Measurable results were satisfactory, since greater savings were obtained than those estimated by the initial plan. For example, the stock in process went from 9,784 items to 2,596 items with a reduction in the size of packages and the *kanban* implementation. There was an improvement of 73%, while the initial estimate was a 25% reduction in inventory in process. By implementing the pad printing cell and packaging changes, it was possible to account for savings of 30% of the area used in processes and stocks once it was estimated an improvement of 15% as target. There was a reduction from four to three direct employees and the production capacity improved 19%, i.e., higher than the 10% desired at the beginning of the project.

The implementation of the pull production system improved response time for the assembly line by 92%, i.e., from 5.3 hours to 0.38 hours, thus making it possible to change a stock in process involving steel wire racks into smaller supermarket plastic boxes. These box-type plastic packages are in the pad printing cell, which is an area next to the assembly line, and are ready to be pulled by the assembly line. The cell works to supply the 12 boxes with items, totaling a maximum of 228 products in the established supermarket. Therefore, it was only after the implementation of basic tools of pull production, for example, a supermarket with families of products, i.e. subsets comprising an evaporator door and defrosting tray that customer service was achieved through an assembly line based on the Just in time concept.

The total manufacturing cycle time has been reduced from 79.5 s to 72.5 s. It was noted that it is possible to eliminate activities that do not add value in a push system when compared to the pull system. This occurred, for example, from eliminating the time to pack items and move packages since, in the case of the pad printing sector, the process was grouped in a cell layout format composed of press, ultrasound and pad printing machines for a continuous flow with no interruptions in the process. By measuring the result achieved on lead time by considering no raw materials and suppliers, it was found an improvement of 72%, i.e., from 8.03 hours to 2.24 hours.

As demonstrated, the current value stream mapping is related to a push system, where a subset of defrosting tray and evaporator door for refrigerators has been produced and there are possibilities for improvement (kaizen). The conduction of these improvements between mistakes and successes by the multifunctional team has changed the way of thinking about the production system over time. After implementing the supermarket pull system, as shown in the future value stream map, it resulted in items being dispatched in less time, with less inventories in process and stored, thus creating a productive and flexible environment.

Such a change from the creation of a manufacturing cell and, consequently, the elimination of the pad printing sector, generated a cultural change in the injection sector, not only as regards the implementation of *kanban* to manage and avoid the lack of materials, but also through the provision of a subsequent implementation of total productive maintenance to avoid machine downtime and enhance the overall equipment efficiency aimed to improve results. There was also a change in the occupation of operators since they started doing activities of pad printing of other injected items by respecting the available time of the machine during which the operator was idle. Such an improvement was estimated and leveraged through the value stream mapping of the supermarket pull system.

Therefore, concepts of Lean Production are linked to the Toyota Production System and aim to constantly improve its organizational systems by eliminating or minimizing the eight types of *muda* (waste). For such a purpose, it is based on five principles (value, value chain, continuous flow, pull production and perfection) that assist in determining activities that add value and those that do not add value which can be identified, analyzed, and improved by a wide set of tools.

The pull production principle not only reduces the stock of in-process and finished products, but it also reduces production costs, in addition to reducing the entire product production cycle, which improves the company's responsiveness to fluctuating customer demands and lowers the time to deliver products.

ACKNOWLEDGMENT

Brazilian Ministry of Health, Fluminense Federal University and Euclides da Cunha Foundation [TED 125/2019, grant numbers: 25000191682201908]; and the National Council for Scientific and Technological – CNPq [grant number 424722/2018-6].

REFERENCES

Aghajani, M., Keramati, A., & Javadi, B. (2012). Determination of number of kanban in a cellular manufacturing system with considering rework process. *International Journal of Advanced Manufacturing Technology*, *63*(9-12), 1177–1189. doi:10.100700170-012-3973-y

Arlbjørn, J. S., Freytag, P. V., & de Haas, H. (2011). Service supply chain management: A survey of lean application in the municipal sector. *International Journal of Physical Distribution & Logistics Management*, *41*(3), 277–295. doi:10.1108/09600031111123796

Chiarini, A. (2013). *Lean Organization: from the Tools of the Toyota Production System to Lean Office*. Springer. doi:10.1007/978-88-470-2510-3

Dennis, P. (2008). *Produção Lean Simplificada - Um Guia para Entender o Sistema de Produção mais Poderoso do Mundo*. Bookman.

Graban, M. (2016). *Lean Hospitals Improving Quality, Patient Safety, and Employee Engagement*. Productivity Press.

Hines, P., Holweg, M., & Rich, N. (2004). Learning to evolve: A review of contemporary lean thinking. *International Journal of Operations & Production Management*, *24*(10), 994–1011. doi:10.1108/01443570410558049

Kaswan, M. S., Rathi, R., & Singh, M. (2019). Just in time elements extraction and prioritization for health care unit using decision making approach. *International Journal of Quality & Reliability Management*, *36*(7), 1243–1263. doi:10.1108/IJQRM-08-2018-0208

Liker, J. (2003). *The Toyota Way: 14 Management principles from the world's greatest manufacturer*. McGraw Hill Professional.

Ohno, T. (1998). *Toyota production system: beyond large-scale production*. CRC Press.

Rother, M., & Shook, J. (2013). *Learning to see: value stream mapping to add value and eliminate muda*. Lean Enterprise Institute.

Smalley, A. (2004). *Creating level pull: a lean production-system improvement guide for production-control, operations, and engineering professionals*. Lean Enterprise Institute.

Spearman, M., Woodruff, D., & Hopp, W. (1990). CONWIP: A pull alternative to kanban. *International Journal of Production Research*, *28*(5), 879–894. doi:10.1080/00207549008942761

Womack, J. P., & Jones, D. T. (2007). Lean thinking: banish waste and create wealth in your corporation. New York: Simon and Schuster.