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Master of Science – Mechanical Engineering

"A Comprehensive Approach to Re-layout Optimization through Simulation: The Ceramic Process Industry Case Study "

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Disclaimer

The data in the following work have been modified from the real ones in order to maintain the corporate privacy of the firm. Nevertheless, the conclusion will not lose their truthfulness. For the industrial privacy, the name of the manufacturers of the machines will not be mentioned likewise any reference to it.

Abstract (English)

When taking decisions concerning layout improvements, lean manufacturing principles can be very helpful, but they are necessary and not sufficient on its own in order to obtain optimal results in term of production flows' optimization and costs' reduction. For this reason, numerous researches define multiple systematic procedures for layout design's approach and, among them, Muther's one is the main representative.These are generally standardized procedures and their aim is the one of generating different layout alternatives and of evaluating them on the basis of a cost function: the main drawback of such an approach is that it only considers the historical flows' projection without taking into account possible changings in the market demand or in the production needs. This is why, if relevant changes in the production mix or in the production volumes are to happen, this methodology cannot generate a satisfying solution. This thesis has the purpose of introducing an integrated approach between the static and dynamic layout analysis, while in literature the DFLP problem has been singularly addressed with various methods (exact ones, heuristic, meta-heuristic and hybrid ones), each one of them has the aim of developing an adequate solution for the reduction of machines' rearrangement costs or material handling costs in various scenarios. The aim of this thesis is proposing a structured decision-making methodology that, starting from lean manufacturing principles, takes also into account different static approaches and combines them with a dynamic assessment of each generated alternative through the use of a simulation software called AutoMod. Finally, some evaluation parameters, as key success factors, will be generated in order to obtain an alternatives' ranking. By generating such a procedure, it will be possible to offer to managers an instrument to be used in every factory or plant when investments on layout improvement must be addressed. The procedure that has been developed in this thesis has been applied in the Geberit ceramic plant in Bromölla, more specifically in the products' inspection department: different layout alternatives have been generated and a final ranking has been obtained, always taking into account the Company's needs. Thanks to such an integrated decision-making methodology, the optimal final solution has been approved by the Company's board and an investment for its realization has been allocated.

Key Words: Lean Manufacturing; Layout Design; Spaghetti Diagram; Systematic Layout Planning; Dynamic Layout Planning; Production Flow Optimization; Ergonomics; Simulation of Production Systems.

Abstract (Italiano)

Quando a livello manageriale si decide di apportare delle modifiche al layout produttivo, i principi della lean manufacturing possono essere estremamente utili, ma, da soli, sono necessari e non sufficienti ad ottenere risultati ottimali a livello di miglioramento del flusso produttivo e riduzione dei costi. A questo proposito, numerose ricerche definiscono varie procedure sistematiche di approccio al layout design e, tra queste, esemplificativa è quella introdotta da Muther. Tali procedure sono generalmente standardizzate e hanno lo scopo di generare diverse alternative di layout e di valutarle sulla base di una funzione di costo: il principale difetto di tale approccio è che considera solo una proiezione dei flussi storici senza tener conto di eventuali cambiamenti della domanda di mercato o delle esigenze produttive. Per questo motivo, se si vuole tenere in considerazione tale variabilità ambientale e di mercato, l'utilizzo esclusivo di queste metodologie non è in grado di supportare una soluzione ottimale. Quello che questa tesi vuole proporre è un approccio integrato tra analisi dinamica ed analisi statica del layout, mentre in letteratura il DFLP è stato affrontato singolarmente con vari approcci (euristici, meta-euristici, esatti e ibridi), ognuno dei quali ha lo scopo di trovare una buona soluzione che possa diminuire i costi di riposizionamento dei macchinari o ridurre il costo relativo al "material handling" in diversi scenari. Lo scopo di questa tesi è quello di generare una metodologia decisionale strutturata che, partendo dai principi della lean manufacturing, tenga anche conto di altri approcci statici e li combini con un analisi dinamica delle alternative generate tramite l'uso di un software di simulazione chiamato AutoMod. Infine, verrano identificati paramentri di valutazione considerati "key success factors" al fine di generare un ranking delle alternative. Con la creazione di tale procedura, sarà possibile offrire uno strumento per i managers da poter utilizzare in ogni stabilimento produttivo o struttura dove siano previsti investimenti sulla modifica o aggiornamento del layout produttivo. La procedura sviluppata in questa tesi è stata applicata al sito produttivo ceramico Geberit di Bromölla, più precisamente nel dipartimento adibito all'ispezione dei prodotti dopo la fase di cottura: varie alternative di layout sono state generate ed un ranking finale è stato prodotto tenendo conto delle esigenze dell'azienda. Con l'utilizzo di tale medotologia decisionale, la soluzione ottimale individuata è stata avvallata dal board dell'azienda e un investimento per la sua realizzazione è stato predisposto.

Parole Chiave: Lean Manufacturing; Layout Design; Spaghetti Diagram; Systematic Layout Planning; Dynamic Layout Planning; Production Flow Optimization; Ergonomics; Simulation of Production Systems.

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Chapter 1: Introduction

The aim of this introductory chapter is describing what the purpose of this project is and setting the work's context. This study comes to life in the framework of a university project called UNITECH.

Figure 1, UNITECH international Association logo

UNITECH is an international program that brings together three worlds: the academic partners, the corporate partners, and the alumni association. In the framework of this program ten students are selected every year from eight different universities in Europe and they achieve knowledges and transversal skills throughout a whole year of experience characterized by an international exchange, in one of the academic partners, and an international internship, in one of the corporate partners. During the UNITECH year the students can travel in different cities of Europe and they strengthen their own personal network with current, past and future alumni and partners. For what concerns my experience inside UNITECH, I have passed through the following partners:

- Home University: Politecnico di Milano
- Host University: Chalmers University of Technology
- Corporate partner: Geberit Group

Figure 2, Corporate and academic partners of the program

The thesis study was born in combination with my internship experience inside the corporate partner that took place in the Swedish Geberit plant of Bromölla. Inside this plant I worked as Process Engineer with the role of improving and optimizing production patterns and flows in diverse areas of the factory. At first, I spent a couple of months in finding solutions for increasing the availability of the robot assembly department and, more than that, I spent time in digitalizing the data collection that was originally not traced at all. For what concerns my second and final assignment inside the factory, after I took some confidence within the job floor, my manager moved me in another department with the aim of applying kaizen intervention to reconfigure the location of workstations in one of the two inspection area of the factory. In the next sub-chapters, I will first introduce the company and later describe in detail what my second assignment was and how I decided to combine it with my academic thesis with the aim of bonding both technical and experience-based knowledge together with my academic education and background.

The Company

Geberit is a Swiss multinational group specialized in manufacturing and supplying sanitary parts and related systems. It is a leader in its field in Europe with a global presence through its subsidiaries.

The Beginnings

In 1874, Caspar Melchior Gebert started a plumbing business in Rapperswil, Switzerland. In 1905, he began to manufacture parts. His toilet tank, the Phoenix, a first, made of lead-coated wood and with lead fittings (particularly a flushing mechanism), was revolutionary and very successful.

Figure 3, Geberit first product "Phoenix"

When Gebert died in 1909 his sons Albert and Leo took over the business. In the following years, the company expanded within Switzerland as well as to neighbouring countries, and added new products (pipes, taps and valves). In the 1930s, the company was a pioneer of plastic parts in the sanitary industry. In 1953, Heinrich and Klaus Gebert inherited control of the company and named it Geberit. The company opened a distribution subsidiary and new branches in Europe, which, besides parts, also offered technical services. As Germany was a growing market, the first international subsidiary was opened there in 1955, in Pfullendorf, which was also going to be the site of the first factory outside Switzerland. Since then, a number of subsidiaries were created in

European countries, including France (1959) and Austria (1965). The company moved from Rapperswil to a larger facility in Rapperswil-Jona and introduced a concealed tank system.

Expansion

In the 1970s, Geberit introduced several new products, such as full drainage systems, flush-mounted systems, and new components for the hygiene sector. A third plant was opened in 1972 in Pottenbrunn/Sankt Pölten, Austria. The company also created subsidiaries in Denmark, Belgium and the Netherlands. The company tried to enter the American market, creating a subsidiary in Michigan, Indiana. However, the U.S. presence remained insignificant for years.

In 1977, the company entered the installation systems market, which went on to become the most important market of the company. In 1980, the German facilities were expanded, and a warehouse complex was opened at its Rapperswil-Jona headquarters. It also acquired a big German player in the installation-elements market, Sanbloc. In 1986, the company started a process of automatization of its production. In 1989, it acquired a stake in FAE Fluid Air Energy, joining the fresh water supply systems sector.

The company manufactures and sells its products mainly under the Geberit brand, although some subsidiaries' brands are also used. It has operations in more than 41 countries.

Geberit's strategy is based on four pillars:

- Focus on sanitary technology.
- Commitment to innovation.
- Selective geographic expansion.
- Continuous business process optimization.

For several years now, Geberit has been pursuing the three-stage sales model and the push-pull strategy. More specifically, Geberit products are distributed wholesale, with the company training over 100,000 plumbers and decision-makers a year at its 25 training centers around the world or at external training courses. To date, Geberit has received a range of awards for the company's innovative strength, product design and its strong focus on sustainability (Wikipedia, 2020).

In recent year Geberit expanded its business in the ceramic sector to complete the product portfolio in the sanitary sector. Thanks to the acquisition of the Finnish Sanitec Group, Europe's leading provider of ceramic appliances, in 2015 the company gained several well-known brands such as Keramag, Ifö, Kolo, Allia and Pozzi Ginori (Geberit Group, 2020).

The Values

Through this acquisition of a range of long-standing ceramic brands, Geberit now has a new look: the reliable technology behind the wall is united with perfectly designed bathroom equipment. With Design Meets Function, Geberit enables end users to experience this new world for themselves and is constantly demonstrating new possibilities for bathroom design.

These values are the foundation of the Geberit brand:

- ***Innovation***: Geberit's product development is based on solid market expertise and the latest technology. They place emphasis on the quality and efficiency of their research and development. That is what enables them to secure their market leadership and set the trends in sanitary technology with their sanitary products.
- ***Partnership:*** Their customers are the focus of their actions. That is why they want to share their know-how and work together to find the best solution. The corporate culture is based on mutual respect as well as open and honest communication.
- ***Know-how:*** Experience and knowledge are at the heart of all they do. Know-how is knowledge that is not only owned, but applied. In daily work, they want to create solutions that make a difference. In their worldwide training centers, tens of thousands of sanitary specialists receive basic and advanced training every year.
- ***Reliability:*** They aim to create durable solutions which stand out for their simplicity. They want to guarantee the safety and durability of their products and systems throughout their life cycles.
- ***Quality of life:*** With their products they want to create an attractive ambience that makes people feel at ease. They set new standards in design, comfort and water management. That is part of their long-term contribution to the environment and society at large.

The Project

After this brief introduction concerning the company and its values, it is now time to describe the project tasks and how I decided to handle it from beginning to the end. As already introduced previously my internship experience took place in the Swedish plant of Bromölla. This plant is in a small village in the southern region of Scania and it is where the biggest Nordic brand in the sanitary sector is produced, the Ifö brand.

Figure 4, Ifö logo

The Plant

The original name of the brand comes from the island located at the center of the lake close by the plant where originally the workers used to procure the raw material. This plant was acquired by the Geberit Group, after 2015 acquisition of the Sanitec Group, and from that day a boost in process optimization and product requalification had started.

Classification of the production system

The aim of this subchapter is to clarify the specific framework of study for what concerns the type of production process that the plant entails. This is important to classify the study into a target family of production processes in order to generate the boundary conditions for evaluating the outcome of the research.

As a first parameter it is useful to analyse the pareto chart of the product mix inside the pant (Figure 5), it is easy to get the immediate understanding that the production is organized mainly on few product considered as "high runners" that make most of the volumes, while several other products (80% of products) are produced in a much lower scale (20% of volume).

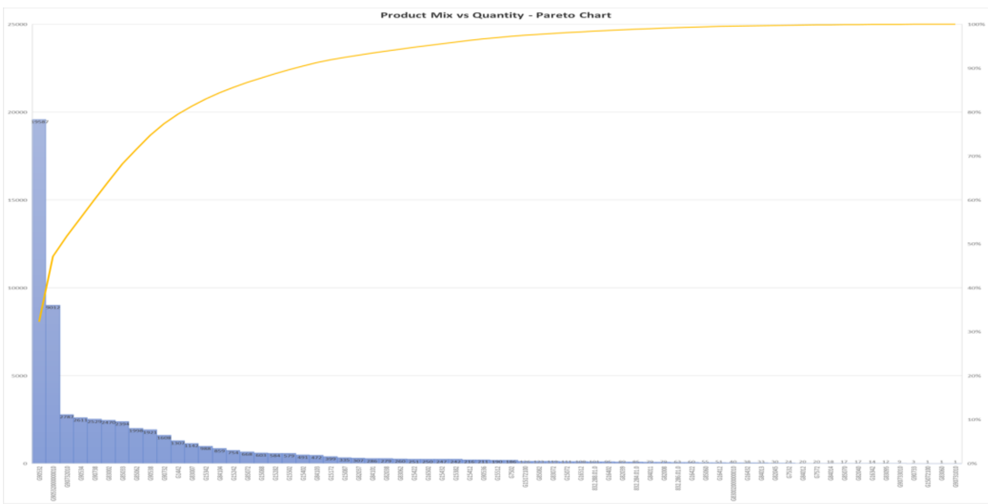


Figure 5, pareto analysis of the production mix

The plant can be classified as a ceramic plant, since the products are all ceramic products that are processed in the same way in a precise pattern. From raw material until finished product, all the operations are performed inside the plant and for this reason it can be defined self-sustaining for the greater part of the process. The process begins with the supply of a raw material called "slip", this material is like sand, and we can define it as:

"A slip is a liquid mixture or slurry of clay and/or other materials suspended in water. It has many uses in the production of pottery, and other ceramic wares" (Wikipedia, 2020)

The slip is then mixed and stabilized in big silos where the right mixture of chemical components is fundamental to get the best result in the sub-sequent process. Once the mixture is stabilized, it is sent through pipelines into the main building where most of the operations are performed. The mixture is then sent to the casting machines where several molds are used for each different product type: in this specific plant the casting is performed in a non-traditional way, meaning that high pressure casting is performed allowing high production volumes and higher utilization. Once the pieces have been casted, they are sent to the drying areas where they must wait from 15h up to 30h depending on the product type. After the drying process, each piece must pass through a glazing station where a specific composition of glaze is distributed on the product's external surface to prepare the product for the high temperatures inside the kiln. Once the pieces have been correctly glazed, they are moved inside one of the three kilns for 18 up to 30 hours depending on how the speed is set. The firing temperature is set around 1162-1240℃ and the pieces have time to cool down slowly while leaving the kiln to reduce the probability of cracks or defects' formation. Once each piece leaves the kilns it should pass through an inspection phase before going to the assembly or packaging area and then shipped inside the fulfilment centre. The pieces that need to be repaired are sent to special glazing stations and then are moved inside special kilns for re-firing that lasts for almost 48 hours.

Several products are designed and produced inside the Bromölla's factory and they can be mainly classified into two first categories, depending on their chemical composition of the clay:

- Vitro China (VC) Models
- Fire Fine Clay (FFC) models

Moreover, within each type of composition there are different product type such as:

- Washbasins
- Tanks
- Bowls

To sum up, it can be said that the plant works continuously 24 hours a day for 7 days a week and all the products follow a similar path through the production chain. Even though the flow is almost continuous the products are casted in a discrete number of batches and each product family follows quite different paths inside the factory. The departments inside the plant are distributed in a process-oriented fashion, but with and hybrid cellular manufacturing approach where some areas are duplicated around the factory to help reducing the complexity of routes and path and improving the overall throughput. The product demand is quite stable and this allows a production based on forecast that brings, as a drawback, a quite high stock of finished goods and a non-negligible amount of work in progress. Moreover, the level of automation is very high with an overall number of robots equal to 54 currently in operation. Automation has a long tradition in Bromölla, with the first robot used for glazing the green bodies back in 1970. In order to remain competitive, production process have constantly been reconsidered, modernized and reorganized.

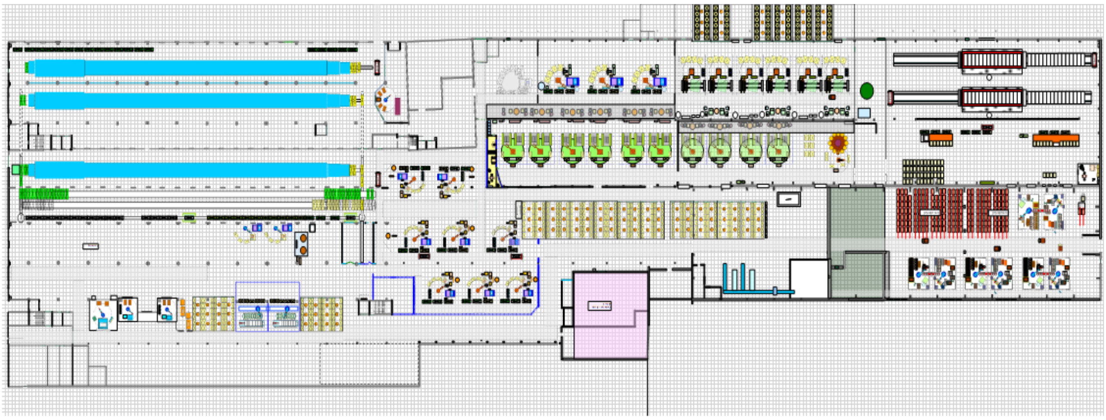


Figure 6, Bromölla's Plant Layout

The Department

For what concerns my task inside the plant, I was assigned, as process engineer, to the Technical development department below the supervision of the Technical Manager of the plant. I was responsible for improving the process performance through optimization of production flows and suggestion of a re-layout analysis of the inspection department out of kiln 21.

The name of the department that needed to be improved is “FFC Inspection”, where FFC stands for Fire Fine Clay: a particular composition of the clay used to cast the ceramic washbasins in the plant. This department has the purpose of inspecting all the pieces that leaves the kiln 21. Originally, only FFC models and washbasins where fired in kiln 21 especially due to a partnership between Ifö and IKEA. As a matter of fact, a whole area of the plant was used to cast washbasins for IKEA with 6 stations for casting, 12 molds and 3 robots overall. In recent years, this partnership ended and today a requalification of the casting and inspection area has been addressed. In particular it is easy to understand how the FFC inspection department was originally designed for the inspection of washbasins only, while today the department is inspecting several other product types such as VC washbasins, Bowls and wall hang bowls. The combination of an old layout design and a high product variety generates congestion during operations and high quantity of work in progress inside the department.

The Layout

For what concerns the positioning of workstations and machines inside the job floor it is useful to identify 10 main areas where most of the operations are performed:

- ***Conveyor Buffer***: here all the pieces enter the department on top of AGVs that by picking up the kiln-carts and dropping them on top of the conveyor rail generate the material input of the department itself.
- ***Inspection Desk A:*** the light blue boxes area close by the end of the conveyor buffer, in this area an operator performs the manual inspection of most of the bowls and high runners’ products.

- ***Inspection Desk B:*** the green boxes area close by the conveyor buffer, on this side the inspection of VC washbasin, wall-hang bowls and FFC (to be glued) washbasins is performed.
- ***Gluing Station:*** immediately after the inspection desk B, it is used to pack the FFC models that need the glue for their packaging.
- ***AGV pallet queue:*** here the good and the repair pallet are positioned once full and a call for an AGV is activated so that they can be transported to the next step in their lifetime inside the plant.
- ***Empty pallets stock:*** here some pallets are stocked in pile and a tool is used to help the operator during the picking of a new pallet after the removal of a full one.
- ***Wrapping Machine:*** it is the machine used once a FFC pallet is fulfilled with packaged pieces and it has the aim of wrapping the pallet with plastic material before moving it to the fulfilment centre and then shipping it to the end customer.
- ***Packaging Station:*** this area is used to pack most of the FFC pieces and it is made of a metal support where the operators position the cardboards already folded and then manually moves each FFC piece inside the box.
- ***Finished goods WIP:*** quite large area used to store the WIP pallets that are not yet full and cannot be wrapped yet.
- ***Cardboard Storage:*** quite big area used to stock all the cardboards material needed for packaging of the pieces.

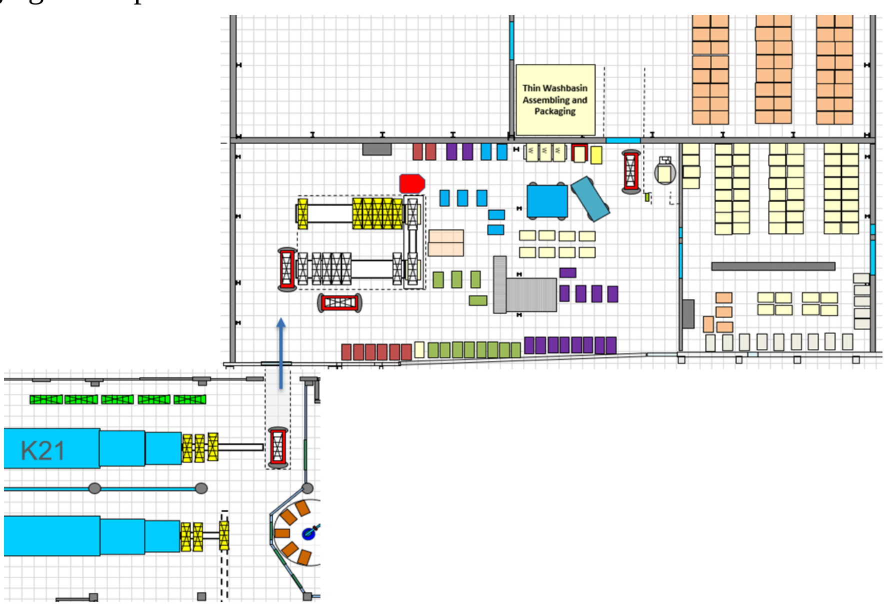


Figure 7, FFC inspection layout

Manpower and Shifts Management

The shifts inside the FFC department are organized as follows: 3 shifts per week time and 2 shifts during the weekend. During the week, each shift lasts 8 hours while in the weekend a shift lasts 12 hours. There are overall 3 operators working in the department, but one of them works only daytime in a specific spot, while the other two work full time. The two main operators must split their work in a flexible way helping each other's: one is performing the inspection, while the other performs all the packaging and material transportation within the working area. During their shifts, the operators have a 15 min break almost every 2 hours of work.

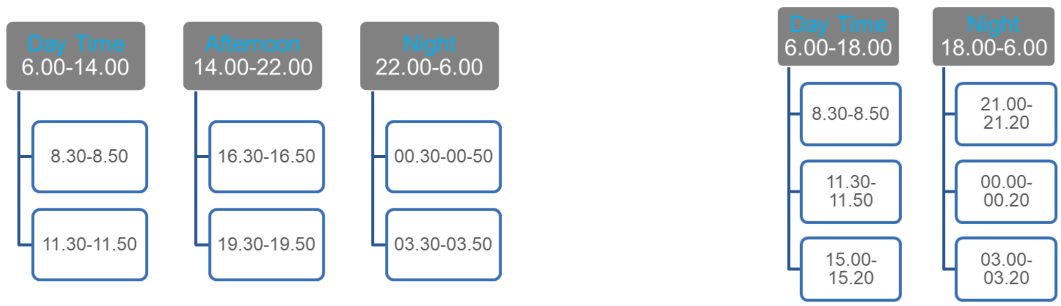


Figure 8, shift management during week time (left side) and during the weekend (right side)

Chapter 2: Lean Manufacturing State of the Art

This chapter aims at describing what are the main principles of lean manufacturing and what its application is when it comes to designing the allocation of departments inside a facility or even the positioning of workstations inside a department. When we deal with the layout design problem, we immediately understand that there is a very high number of articles and literature arguing about techniques, algorithms, and tools to be used in order to achieve the best possible layout designs. Most of these tools are quantitative procedures that, depending on the constraints, can give locally optimal solution or globally relevant alternative generation. What can be also seen, is that lean manufacturing generated the basis for the collection of all the input that are necessary for a broad and complete layout analysis, but before entering into details, it is worth to introduce some definitions.

History and Definition

The Lean Manufacturing concept comes from “The Toyota Way” (Toyota Production System, TPS, 1930). The term was coined in 1988 by John Krafcik and a first definition can be find later in 1996 where five key principles where addressed: 'Precisely specify value by specific product, identify the value stream for each product, make value flow without interruptions, let customer pull value from the producer, and pursue perfection.' (Womack and Jones 1996).

In the Japanese post-war economy, levels of demand were low and large scale, with low cost production, had little space. For this reason, a new concept of scheduling production raised, the so called “Just in time”. The characteristic of this new concept was developed by Taiichi Ohno and concerned the aim of pulling demand directly from the customer instead of pushing the products (Key Principles & Waste). This new revolutionary way of producing brought several advantages including low or almost zero work in progress, flexibility in the production mix and reduction of wastes in every form.

The concept of lean has been interpreted in different ways in the literature [1] . Hines et al. (2004) suggest that lean has both strategic and operational dimension. Shah and Ward (2207) describe lean as having both philosophical and practical orientation, which are embedded in three levels of lean thinking: philosophy, principles and, tools and techniques [2]. As shown in Figure 9 the topmost level is the philosophical level that expresses the core concern of lean. According to lean thinking, any business activity that does not create value from customer perspective is a waste, thus, needs to be eliminated or minimized.

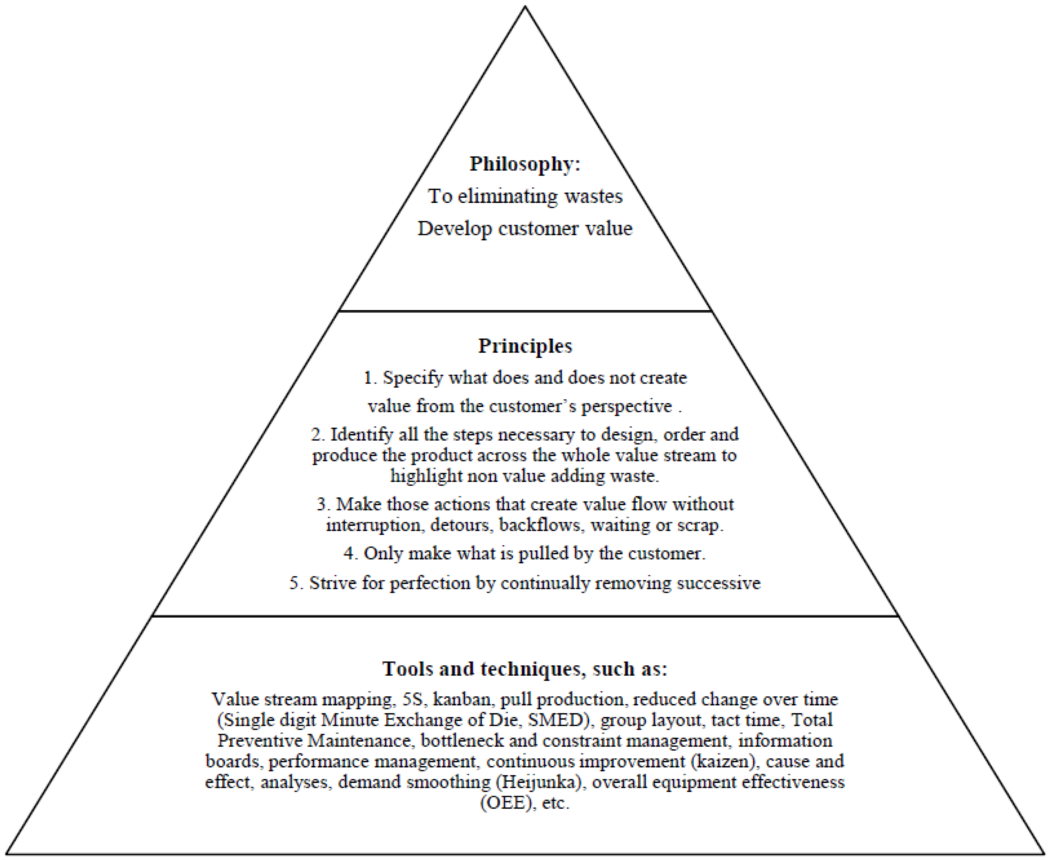


Figure 9, Three levels of lean source: (Arlbjorn J. S., 2008)

Womack and Jones define Lean as "...a way to do more and more with less and less - less human effort, less equipment, less time, and less space - while coming closer and closer to providing customers exactly what they want" and then translate this into five key principles:

1. Value - Specify the value desired by the customer. "Form a team for each product to stick with that product during its entire production cycle", "Enter into a dialogue with the customer" (e.g. Voice of the customer)
2. The Value Stream - Identify the value stream for each product providing that value and challenge all the wasted steps (generally nine out of ten) currently necessary to provide it
3. Flow - Make the product flow continuously through the remaining value-added steps
4. Pull - Introduce pull between all steps where continuous flow is possible
5. Perfection - Manage toward perfection so that the number of steps and the amount of time and information needed to serve the customer continually falls into the market based on forecasts.

Value and Non-Value-Added Activity

In order to identify the value that a process brings to the final product, it is extremely important to address what, in lean thinking, are defined as *Muda* that is the Japanese word for wastefulness or futility. The main source of waste has been classified in Toyota's Seven Forms of Waste [3]:

1. Transport: moving products that are not actually needed to perform the process
2. Inventory: all components, work in progress and finished products not being processed
3. Motion: people or equipment moving or walking more than is required to perform the processing
4. Waiting: waiting for the next production step
5. Overproduction: production ahead of demand
6. Over processing: resulting for poor processing or product design creating activity
7. Defects: the effort involved in inspecting and fixing defect

Once these wastes are searched and identified inside the plant and through the whole production chain, they must be sorted into what Ohno defines as two different types of Muda:

- Muda Type I: non value-adding, but necessary for end-customers. These are usually harder to eliminate because while classified as non-value adding, they may still be necessary.
- Muda Type II: non value-adding and unnecessary for end-customers. These contribute to waste, incur hidden costs, and should be eliminated.

This classification and distinctions are fundamental when it comes to deciding what must be improved inside the factory and how it must be done, with the final aim of reducing operational and process related costs.

Kaizen and the concept of continuous improvement

As described in the previous chapter, lean manufacturing entails the goal of reaching perfection by eliminating wastes inside the process. This way of thinking and managing resources affects all the production chain and even crosses organizational boundaries with the consequence of affecting the supply chain management and logistics. In order to keep chasing the highest standards, companies need to implement the so-called *Kaizen* concept; this means that business activities must continuously improve all departmental units by involving employees from senior management to operators in the assembly line. *Kaizen* activities can be classified in four steps:

1. ***Point Kaizen***: It is one of the most commonly implemented types of kaizen. It happens very quickly and usually without much planning. As soon as something is found broken or incorrect, quick and immediate measures are taken to correct the issues. These measures are generally small, isolated and easy to implement; however, they can have a huge impact. In some cases, it is also possible that the positive effects of point kaizen in one area can reduce or eliminate benefits of point kaizen in some other area. An example of point kaizen

could be a shop inspection by a supervisor, and he finds broken materials or other small issues, and then asks the owner of the shop to perform a quick kaizen (5S) to rectify those issues.

2. ***System Kaizen***: System kaizen is accomplished in an organized manner and is devised to address system level problems in an organization. It is an upper level strategic planning method which results in a number of planned kaizen events over a long period of time. It contrasts with point kaizen which generally happens as a result of identification of a small issue which is resolved in a short period of time.
3. ***Line Kaizen:*** Line in this context refers to a structured spreading of Lean from point or discrete to the line. For example, kaizen might be applied to a process (point), but also to the downstream process. Those two points constitute a line kaizen. Another example might be in Lean implemented in procurement, but also being implemented in the planning department. Here in this case, planning is upstream from procurement and kaizen is performed at those two points, which thus forms a line
4. ***Plane Kaizen***: It is the next upper level of line kaizen, in that several lines are connected. In modern terminologies, this can also be described as a value stream, where instead of traditional departments, the organization is structured into product lines or families and value streams. It can be visualized as changes or improvements made to one line being implemented to multiple other lines or processes.
5. ***Cube Kaizen:*** Cube kaizen describes the situation where all the points of the planes are connected to each other and no point is disjointed from any other. This would resemble a situation where Lean has spread across the entire organization. Improvements are made up and down through the plane, or upstream or downstream, including the complete organization, suppliers and customers. This might require some changes in the standard business processes as well.

It is important to highlight that in order to apply this continuous improvement approach in the workplace, the commitment should be high involving every part of the production including operators, management and board. Another important aspect to discuss is related to the definition of *point kaizen:* sometimes companies believe they are applying continuous improvement techniques in the right way, while instead they are only applying what in maintenance is called ‘fix and repair’ approach. This means that, in the short term, local optimal solution can be certainly helpful but, if there is not a systematic expansion of the lean approach through all the organization, long term benefits and improvements could be lost. The reason is related to the difference between local and global optimum solution. For example, if we want to improve the output of our production plant and we decide to switch the location of two machines or two departments, since in the current situation this will bring benefits, we should also ask ourselves how this change will affect the rest of the factory. The result of the change should be evaluated not only in the next period, but even in a different possible future scenario to be sure that the solution adopted is not only global, but also dynamic.

The Pull Strategy

Part of the innovation brought by the lean approach in production systems depends on the so called 'pull strategy'. This strategy consists in the idea that production should be driven directly from the customer demand, instead of being pushed into the market (Fig.10).

Let's now define the terms involved:

- Push: As stated by Bonney et al. (1999) control information flow is in the same direction of goods flow
- Pull: Succeeding node makes order request for preceding node. Preceding node reacts by producing the order, which involves all internal operations, and replenishes when finished.

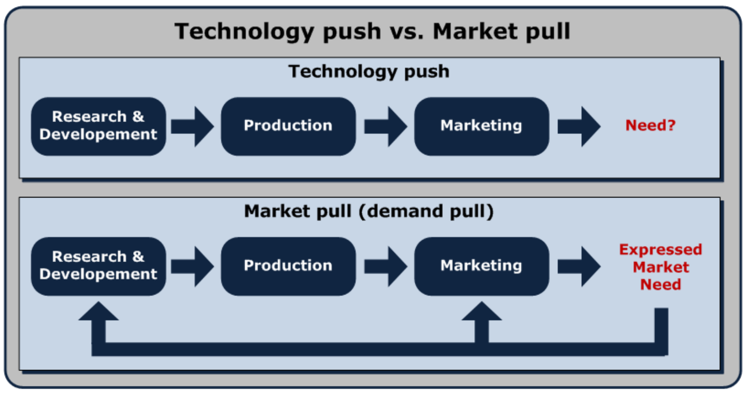


Figure 10, Push vs Pull

The logic behind the *push strategy* is related to standardizing the production pace based mainly on historical data and demand forecasting. This approach leads to a higher capacity in terms of production volumes, but is not a good strategy when it comes to facing a change in the demand, since the information flows in parallel and in the same direction of production. Meanwhile, a leaner approach that addresses a *pull strategy* means that the information flows in the opposite direction with respect to production. For this reason, *Kanban* are used to exchange information moving from the end of the production line upwards. The innovation that this approach brought during the end of the 20th century was mainly related to the reduction of work in progress between production steps and workstations and to the reduction of costs of stocked finished goods in the fulfilment canters, but also related to the great improvements in terms of flexibility and ability to tackle change in customer demand. It is important to clarify that addressing a pull strategy does not necessarily mean a "make to order" kind of production. Toyota Motors Manufacturing is always used as an example and yet the addressed 'supermarket model' approach in which a small inventory is kept and replenished as consumed: in this example Kanban's cards are used to address when there is the need to replenish the consumed items.

Lean Manufacturing Tools and Layout Design Improvement

At this point it is interesting to address how the lean working approach finds its usefulness in the layout design improvement. There are no written rules on how to approach the layout problem with the lean manufacturing method and this depends also on the fact that lean is more a working philosophy than a procedure itself. This implies that some rules and practical tools can be derived from the lean way of thinking, but different ways can be used to find interesting improvements in the positioning of workstations, operators, and machines inside a job floor.

It the next sub-chapters different lean manufacturing tools are described and each of them is analyzed to get an understanding of how it could be applied and what is its need in the layout design improvement, but before that a resume of the lean manufacturing philosophy and approach is presented in Figure 11.

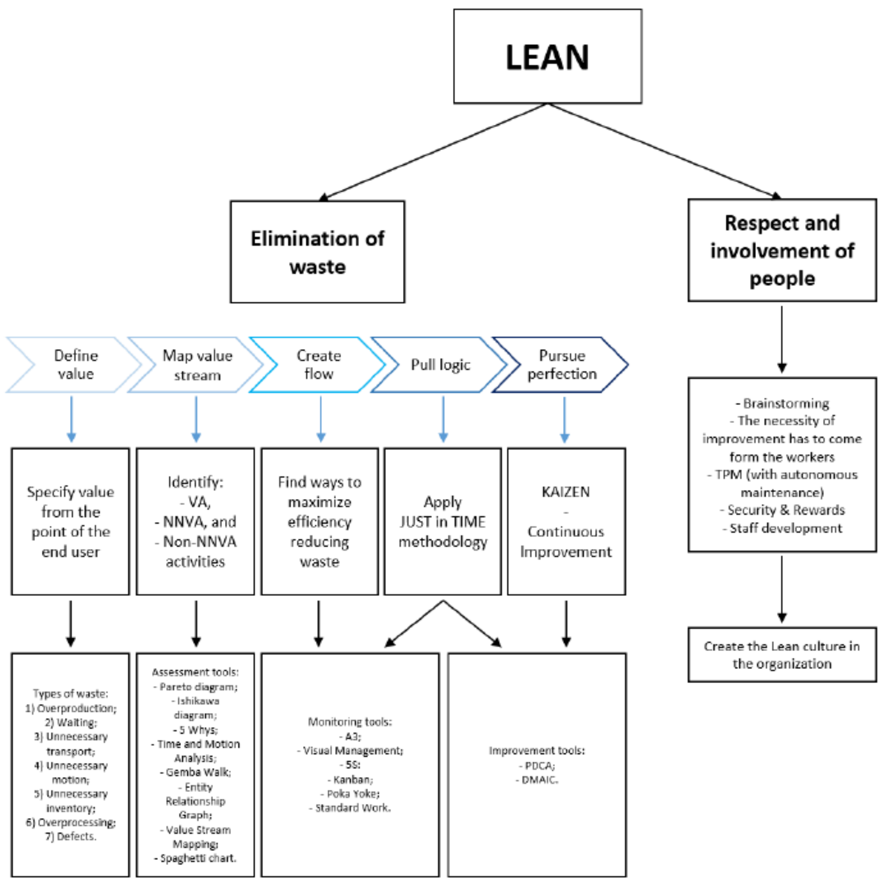


Figure 11, Lean approach resumed (Luigi Paracchini Master's Thesis, 2019)

Pareto Diagram

The Pareto Diagram or also known with the name of 80-20 diagram, is a graph where individual values are represented in descending order by bars, and the cumulative total is represented by the line. The chart is named for the Pareto principle, which, in turn, derives its name from Vilfredo Pareto, a noted Italian economist. The purpose of the Pareto chart is to highlight the most important among a (typically large) set of factors. It can find its application in a wide range of subjects including maintenance, quality control and economics.

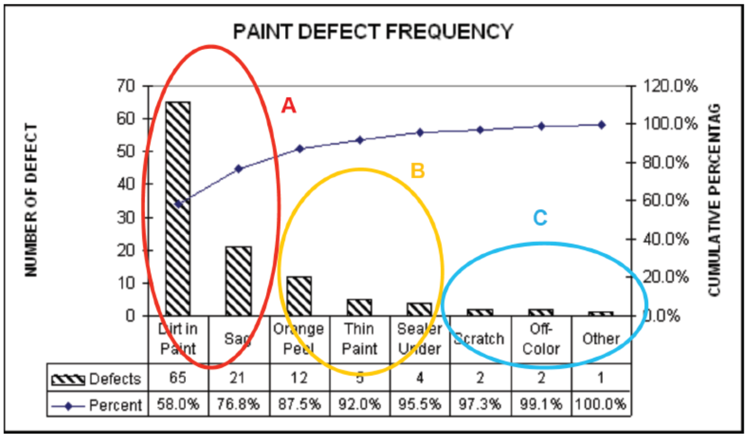


Figure 12, Pareto Diagram

5 Whys

In order to analyse the cause-effect relationship between uncertain events this toll can be very useful. It basically consists in asking "why" enough times until you understand all the root cause of each symptom of a problem.

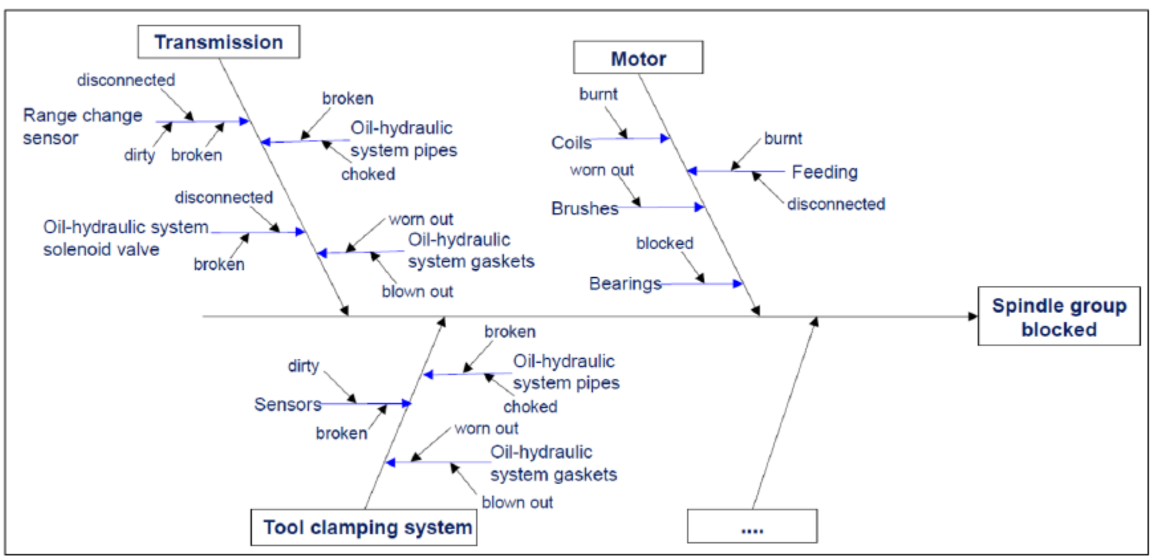


Figure 13, 5 WHYs method

Chalk Circle

One of the famous teaching methods by Taiichi Ohno is the chalk circle. The method itself is simple. A circle is drawn on the shop floor near a point of interest. A disciple is put in the circle and told not to leave it until he is picked up again by the teacher. It can be used for teaching ,but it can also help you to understand a problem in more detail. Pick an area and observe. Expect to invest multiple hours for a true understanding.

Gemba Walk

Gemba is a Japanese term meaning "the actual place", it refers to the place where value is created. Gemba walk means going physically in the studied environment to identify issues and understand their impact on the process. The idea is that problems are visible, so looking around, asking questions, and observing how the processes are carried out are activities that allow managers to look for waste and opportunities.

Value Stream Mapping

As well described in *Kaizen, The Key to Japan's Competitive Success* the practice of value stream mapping (VSM) is to plot the course of raw materials and services connected with the process through the delivery of the finished goods. In general, thanks to this tool a good description of the as-is status can be made addressing the time that each product spends during the process and dividing the waiting time from the actual value adding time. For the good description of the current status improvement can be made, and for this reason a future and 'ideal' value stream should be developed to generate a to-be process with no reduced wastes. The key point to construct an ideal and desired scenario is to focus on constructing a process where the various operations add value to the final product. The idea behind value stream mapping is to provide a visual pictorial representation of what is going on, supported by numerical analysis in order to enable others to evaluate performance.

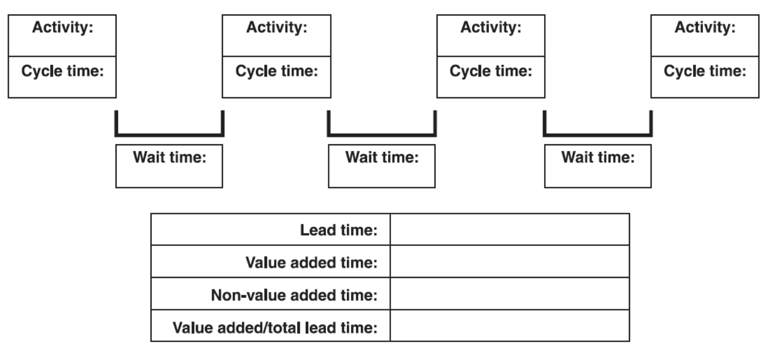
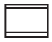


Figure 14, Value Stream Mapping

The nomenclature for the value stream mapping is standardized in order to have everything easy and comprehensible as shown in Table 1.

Table 1, Nomenclature for value stream mapping: basic symbols

	This is referred to as a process box and covers the task being performed at that stage of the process. This can be a technical equipment function or a data related function
	This is referred to as an information box and carries information that is transmitted along the value stream
	This arrow covers the material that is moving along the value stream from supplier to customer
	This arrow covers 'manual' transmission of information
	A broken-line arrow covers the 'push' of materials along the value stream
	Refers to inventory that is stored and covers raw materials, WIP (work in progress) and finished goods/product
	Covers supplies and customer
	Starburst identifies opportunities for Kaizen improvements
	Clouds are used to denote possible solutions
	Denotes the transmission of information/data electronically
	The truck symbol denotes a transport/delivery function
	Use of swimming lanes is often used to denote a task that may be done by specific functional departments – e.g. Technical Operations, QC, QA, Maintenance
	Denotes that material is called for using a Kanban signal
	Denotes the storage if WIP inventory in a controlled area called a supermarket
	Used to identify the lead time for each individual component of the process flow. Each indented section would normally include a time period which denotes the time for that particular step

As with any process map, it is the layout of the basic process flow that is being charted. However, in the value stream mapping there must be included the specification of whether an activity is or is not adding value to the process. In this case it is extremely important to evaluate each activity based on the customer perspective, in order to assure high quality standards and effectiveness in the improvement. The last part of the value stream mapping procedure is related to production of a *scoring card* as show in Fig.12, that aims at checking the performance and benchmarking the solutions.

Table 2, Box score

Metric	Current State	Future State
Total lead time	26.5 days	2.0 days
Value creating time	160 seconds	250 seconds
Changeover time	10 minutes assembly	1 minute assembly
Uptime	80% fill process	100% fill process
Scrap work	6%	<0.2%
Inventory	20000 vials	2600 vials
Fill rate/vial batch	20 hours	8 hours

The box score is a summary chart which records key performance measures for the process being studied, generally box scores will display total lead time and value added (VA) and non-value added (NVA), times for that step.

DMAIC – Define Measure Analyze Improve Control

This tool is part of the Six Sigma methodology frequently adopted to reduce the waste that occurs due to bad quality performance and production variability. This tool helps in problem solving when it comes too reducing or removing wastes caused by defects due to variances in the manufacturing process.

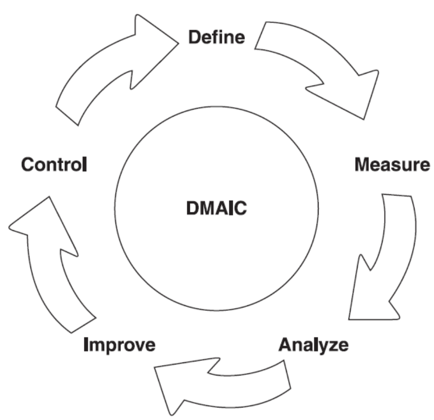


Figure 15, DMAIC cycle diagram

D refers to what is the definition of the problem.

M refers to how the measurements are performed in order to get the required data to perform the ongoing analysis.

A refers to the analysis of the data previously collected by means of different statistical tools. During this phase a distinction can be seen whether the data are randomly distributed or if there's a pattern, important to be noted is that if data are random a Six Sigma solution of the problem doesn't exists.

I stands for improvement made to the process based on the previously developed analysis.

C refers to the control phases that are established in order to maintain sustainable performance through standardized data collection and analysis.

This DMAIC procedure of problem solving is close to what is called PDCA cycle developed by Dr. W. Edwards Deming who laid the bases of much of today's quality control.

Steps definition in Lean methodology:

- *Define*: define the customer demand required and specify the process lead time to meet that need.
- *Measure*: map out the process and data flow involved in the process.
- *Analyze*: express in terms of process efficiency and numerical cycle quantification.
- *Improve*: recognize the process flow patterns and eliminate the waste in the system.
- *Control*: develop mechanisms to appropriately design the workflow to avoid waste introduction on new problems due to these specification errors.

Several useful tools are used in DMAIC analysis, for example: fishbone (Ishkawa) diagrams, SIPOC analyses and critical success factor for process (CTX).

PDCA – Plan Do Check Act

First introduced by Deming it is quite like DMAIC procedure and it infuses the Lean concept of continuous improvement (Kaizen) into the process manufacturing methodology operational framework.

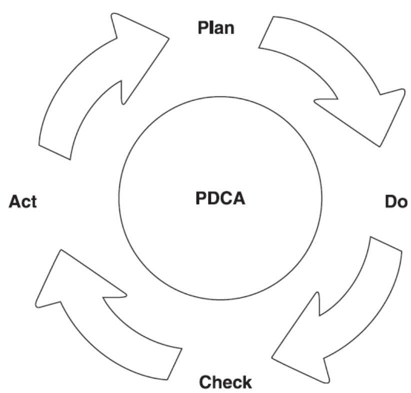


Figure 16, PDCA cycle diagram

If we break down each phase of the PDCA method, we get:

- **Plan**: it concerns the identification of what needs to be changed during the Kaizen event. It also refers to the definition of the procedure that will determine what the new state will look like.
- **Do**: it refers to the implementation of the plan through testing, in order to see what result could occur.
- **Check**: phase in which the results of the change are analyzed. Checked and verified to make sure that the outcome I an improvement with respect to the existing state.

- **Act**: it refers to the broader deployment of the plan and any change needed to make the plan sustainable This could involve the update of existing operating policies and procedures and the related training to assure successful outcomes.

This methodology is very successful when the focus is on removal of one waste element at the time. Kaizen continuous improvement through the help of PDCA procedure is most performing when successive incremental gains are obtained as opposed to trying to solve everything all at once. The idea is to unpack the big picture from one big single problem, to a lot of smaller problems that are much easier to be solved individually. In order to achieve this objective, the team involved in the project must spend time in what in Japanese is referred as ‘Gemba’, meaning the place where the activities involved in the change actually take place.

Spaghetti Diagram

This tool is incredibly useful once a flow chart of the process has been already developed. It is a graph that helps in following the path made by any object, person or information within the factory. By following every step of the product inside the plant for example we could get the precise ideas of which are the movement that are done daily and in particular we could see which of these movement are to be classified as ‘Muda’, and consequently which of those could be eliminated to make the process leaner.

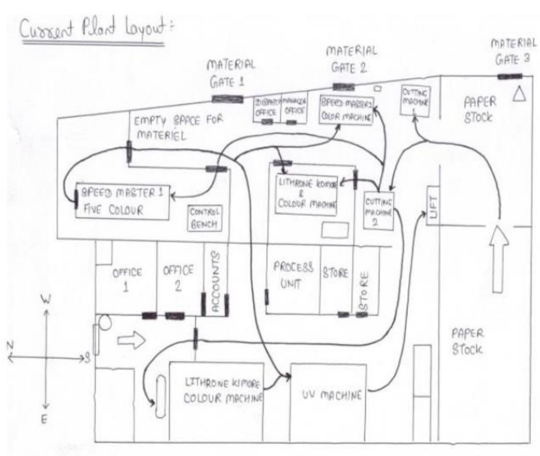


Figure 17, Spaghetti Diagram

Another important feature of the Spaghetti Diagram is that it is very simple to be performed and the result is quite intuitive to be analyzed. As we can see in Figure 17 the diagram can be handmade on top of a layout-s blueprint of a certain plant or a specific department. Only a pen and a good observer are needed to trace the precise movement that an operator or an object is performing during a certain shift or time lapse. This tool is as simple as powerful since from the final outcome of the drawing we can see how many meters have been walked and which movement accounted for the highest amount of steps, also depending on the value that those movements are actually adding to the process from the customer perspective. Of course also other more precise and complex ways of simulating realistic walk paths have been studied [4] to better predict planning models based on operators movement in assembly lines or job floors. These models help in increasing the quality of simulation improving the realism and naturalness of motion, although they are quite time consuming and complex to be modelled and generally such a level of detail is not needed when aiming at a cost-effective solution in real practice of firm's working environment.

The aim of applying a Spaghetti Diagram in the framework of layout design optimization is related to the need of redesigning the operations and the locations of departments in order to generate a much more compact flow. By comparing different alternative Spaghetti Diagram, you could benchmark both quantitatively and qualitatively which of the solutions is better as you can see in Figure 16, where two alternative operation routes are compared before and after including a mobile cart-assisted stocking [5].

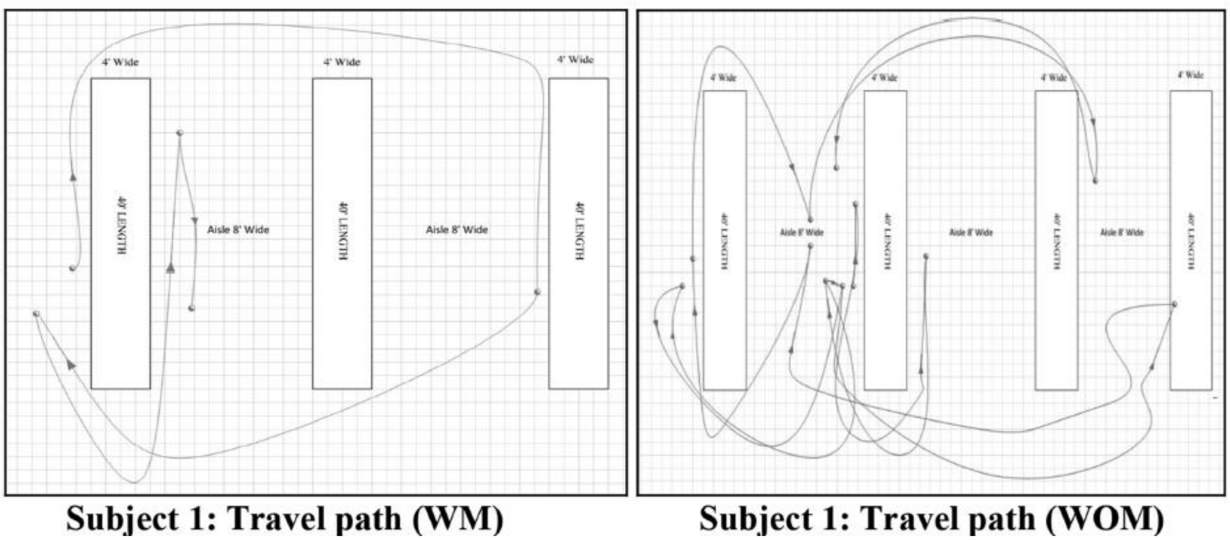


Figure 18, Spaghetti Diagram benchmarking between solutions with or without mobile cart-assisted stocking

By looking at this example one can already tell that the solution without cart-assisted stocking (WOM) has higher redundancies in the path flow while the other solution (WM) has an optimized flow. This kind of analysis can be performed in order to reduce the path walked by the operators and consequently to increase ergonomics of the work conditions of the operators inside the plant or fulfillment center.

The 5S tool

This tool is one of the most basic ones and it is used directly in the workstation to produce a fast-lean transformation. This tool is particularly powerful since it brings to a condition which is conductive to visual control mechanisms and methodologies and lean operations. The name 5S strands for:

- **Sort**: looking at the operations and deciding what to keep and what to discard because it is not being used. The objective is increasing the total 'in use' equipment layouts and increase operations efficiency.

- **Stabilize/ straighten**: Once equipment is sorted the next step is to straighten and stabilize the new operating set-up so that it will be available for use. This phase includes making sure that all the tools, parts, supplies and documentation to support the operation are available and ready at the workplace.
- **Shine**: Clean and maintain equipment, keep surfaces painted and free from scratches and chips, clean and sanitize the process flows, walls and ceilings as required to obtain operational effectiveness. It has been widely demonstrated that the time spent in cleaning operations is much less with respect to the time that the firm would lose in quality checks and production delays due to lack of cleaning.
- **Standardize**: the next step concerns a clear division of roles and tasks during operations. Everyone must have clear understanding of how things are supposed to function and what everyone's responsibility is in the process. The predictability allows a pace to be set for the production cycle which ideally will be matched with the expectation of the customer. As a matter of fact, all personnel involved in the manufacturing plant should function between 65/70% of their normal working day doing standardized work.
- **Sustain**: Sustainability is probably the most difficult element to be implemented for any process, Lean or otherwise, but it needs to be the most basic requirement in order to get the most effective, efficient and compliant process the company can operate. The hardest barrier to this step is related to the energy and motivation needed from the workforce to keep focused and energized to assure constant performance.

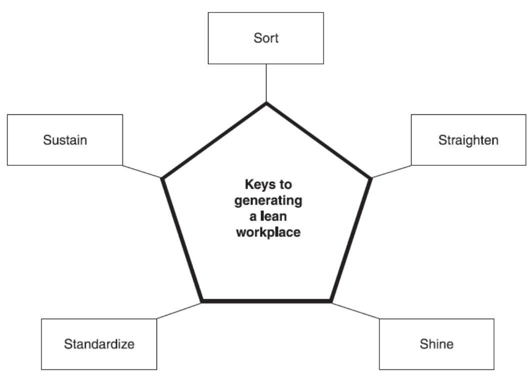


Figure 19, 5S tool

Chapter 3: Facility Layout Planning State of the Art

This chapter will be a collection of literature research and current state of the art in the field of Factory Layout Planning (FLP). The chapter will introduce the main theoretical concepts regarding the layout and re-layout problem in past and modern years. Before introducing the way the layout problem has been addressed in past years, it is necessary to recap some of the main definitions and terminologies that are used in this field and also a little bit of history of the layout design problem. Moreover, the concepts related to the *layout problem* are address though an analysis of the state-of-the-art literature and by accounting for past, current, and future trends. The two main approaches regarding *static* and *dynamic* facility layout planning are discussed and compared in their basic aims and objectives. Finally, the main tools and methods, that have been studied and developed in operational research, are explained with their strength and weaknesses.

History of the facility layout problem

Since early years in human history, the *layout design problem* as been of interest for many different fields of application. From the construction of cities, buildings, streets, or hospitals the understanding of how allocating space and resources in the "best fitting" way is what characterizes this topic. Probably, finding its first structured applications within military and defence application, the layout design problem finds recent application in a broad range of very innovative research fields such as the nanotechnology ones and lithography of microchips.

What does it mean finding the "best fitting" when addressing the layout problem? To answer this question, it is necessary to introduce some definitions:

- ***Facility*** is defined as: "An entity that facilitates the performance of any job. It may be a machine tool, a work center, a manufacturing cell, a machine shop, a department, a warehouse , etc." [6]
- ***Layout*** is defined as: "The way something is arranged" (Cambridge Dictionary, 2020) or "The way in which different part of something are arranged" (Macmillan Dictionary, 2020).
- ***Facility Layout*** is defined as: "It is the arrangement of everything needed for production of goods or delivery of service" [7].

Learning how to physically allocate the resources has many advantages, mostly in operations management where total operating expenses can be reduced up to 50% thanks to a good placement of facilities [7]. Moreover, it has been estimated by Tompkins, White and Bozer (2003) that in the United States, every year since 1955, about 8% of the gross national product (GNP) has been spent on new facilities and, with the continuous improvement concept that companies have adopted, more than 250$ billion for re-layout issues annually. Coming back to the question on how a solution should be defined as “best fitting”, generally literature evaluates layout solutions based on a key parameter or cost function that need to be optimized , such as material handling cost or transportation cost. The aim of this project is proposing a systematic procedure where more than one criterion is considered for the final decision, a ranking of multiple parameters is performed, and a final evaluation of each layout solution is given. What can be said, is that research does not usually agree with a common and precise definition of *layout problem.* Most articles and studies, in fact, deal with the concept of *static layout problem* (in opposition to the *dynamic layout problem* that will be discussed further).

This class of problems was first introduced by Tjalling C. Koopmans (1957): facility layout problem was defined as a common industrial problem where the objective is to configure facilities, so as to minimize the cost of transporting materials between them. Gau & Meller (1999) consider the layout problem, as a non-overlapping planar orthogonal arrangement of *n* rectangular facilities inside a given rectangular area so as to minimize a distance-based measure. Azadivar & Wang (2000) define the facility layout problem as the procedure for finding the relative location for the available space among a give number of facilities. Lee (2002) stated that the facility layout problem consists in the arrangement of *n* unequal-area facilities with different sizes within a given space constraint, which can be linked to length or width of the site area so to minimize the total material handling cost and slack area cost. Finally two more authors, Shayan & Chittilappilly (2004), defined the facility layout problem as an optimization problem that aims to make layouts more efficient by taking into account several interactions between facilities and material handling systems while designing layouts.

In general, layout problems can be classified differently, based on factors such as: the workshop characteristics, how the overall problem is formulated, and the approaches used to solve it. In Figure 17 it can be found a picture taken from the literature analysis concerning the layout problem developed by Drira et al (2006) where a rough tree representation of the different factors taken into account in the literature is presented.

Dynamic Facility Layout Planning

Whether you are planning how to arrange machines inside a department or peoples in a train station, there will always be the need of accounting for future changes and unexpected events. Nowadays the uncertainties in product demand and the highly competitive market in which companies need to grow, brings the need of addressing the planning phase in a smart way. Most of the literature in the early years of the studies concerning the *layout problem* addressed how to improve the layout based on status of production mix and demand. This means that several tools have been developed and tested to find the best arrangement of resources. Page (1991) reported that on average, 40% of the sales of a company derives from new products. This brings changes in product mix and yields to modify the production flow thus affecting the layout composition. Gupta & Seifoddini (1990) stated that 1/3 of the USA firm’s undergo major reorganization of production facilities every 2 years.

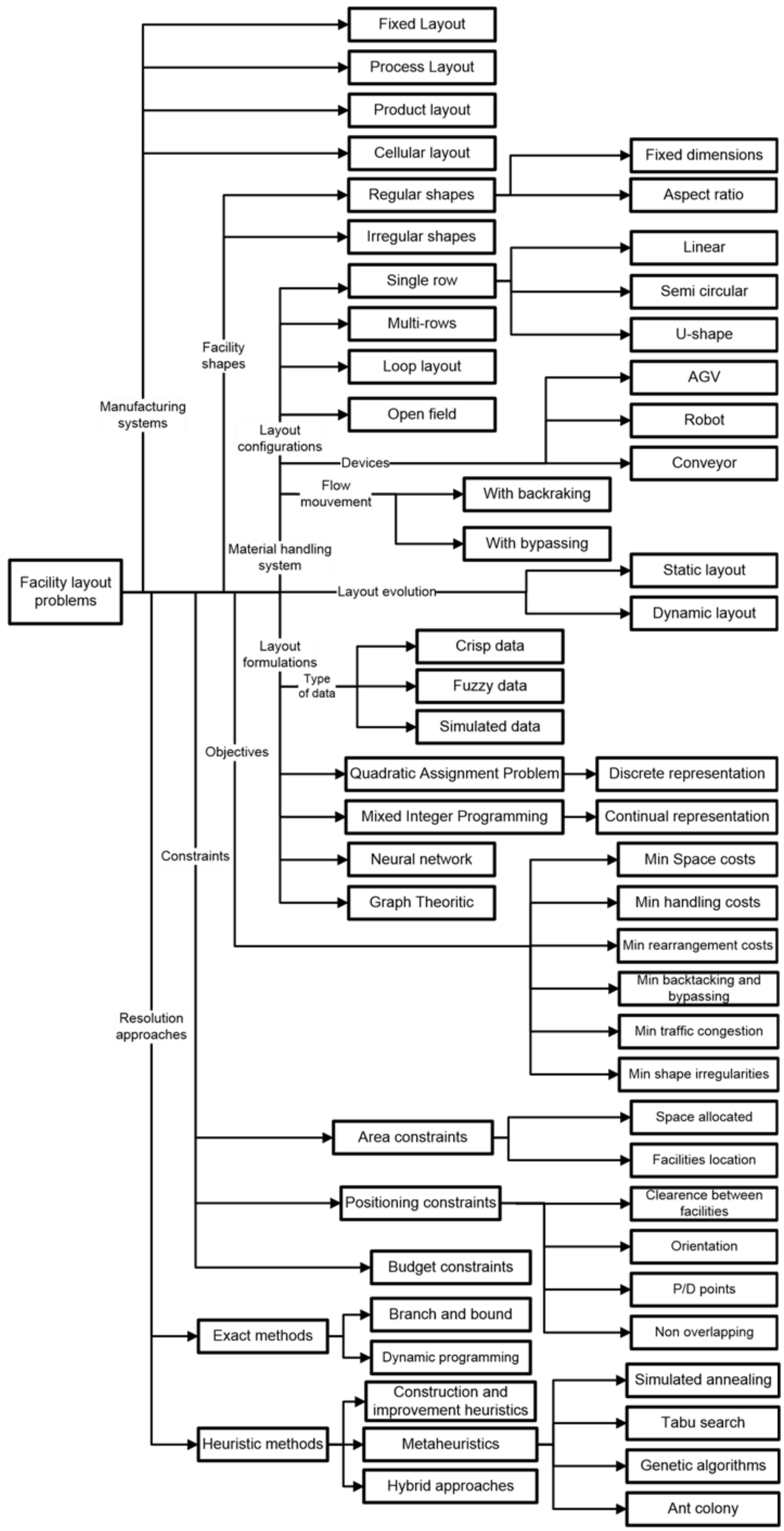


Figure 20, Tree representation of the layout problems [7]

It is important to clarify the meaning of words before entering details, for this reason let us define what is the meaning of static and dynamic facility layout planning in this study:

- ***Static Facility Layout Planning (SFLP)***: it can be classified as a specific phase within the facility planning process and it concerns the placement of departments, equipment, and storage areas inside a facility in a single period of time. It is a specific name for describing the common approach to the facility layout problem when the boundary and input conditions are considered fixed in time.
- ***Dynamic Facility Layout Planning (DFLP)***: It can be defined as an extension of the usual SFLP problem by considering the changes in material handling flow over multiple periods [15].

It is extremely important being able to statically assess how to improve or re-design a plant, based on a current scenario and the higher the quality of this assessment the better will be the outcome in terms of project results and operations performance. Of course, the step ahead and what the current literature has been focusing in the recent years, is understanding how to address the layout problem in multiple scenarios or multiple periods. This approach is categorized as a *dynamic* analysis of the problem since the main idea is planning an horizon divided into periods that may be defined by weeks, months or years. Drira et al. (2006) describe that for each period the estimated flow data remains constant and consequently a layout plan for the dynamic layout problem consists of a series of layouts each layout being associated with a specific period. The consequence of this analysis is a trade of optimization between the material handling costs and the rearrangements cost. Of course, this kind of analysis may not be relevant in every context. As a matter of facts, when a difference between material handling cost and rearrangement cost is too high, two extreme cases are to be discussed:

1. *Material handling costs are much higher than rearrangement costs*, in this case the layout can be redesigned when necessary, if changes in the demand occur, without any prior planning [16].
2. *Rearrangement costs are much larger than material handling costs*, then the same layout for the entire planning horizon might be used [17].

The main difficulty in dynamic facility layout problem (DFLP) has been to estimate future production patterns and condense them into a few discrete scenarios [18]. For this reason, *stochastic facility layout problem* will be discussed in further as another approach to address uncertainties and evaluate the robustness of a layout alternative. Now that a distinction has been made between what we called SFLP and DFLP it is useful to go through the formulation of the main solution methods that have been address in the recent and past literature.

Formulation of the problem

The formulation of static and dynamic layout problems generally relies on various principles, including graph theory or neural networks. The major part of the researchers tried to address the optimization problem, with single or multiple objectives. These formulations can correspond with *Quadratic Assignment Problem* (QAP) and *Mixed Integer Programming* (MIP) that are the most commonly formulation methods used as stated in Drira et al. (2006) literature analysis upon the facility layout problem.

Quadratic Assignment Problem approach

In the QAP the layout formulation is discrete as it can be seen in Figure 21. The facility is divided into equal size rectangular blocks, and each block represents a workstation or a department depending if it is a block layout analysis or a detailed layout analysis. If departments have unequal area they can occupy different blocks [11].

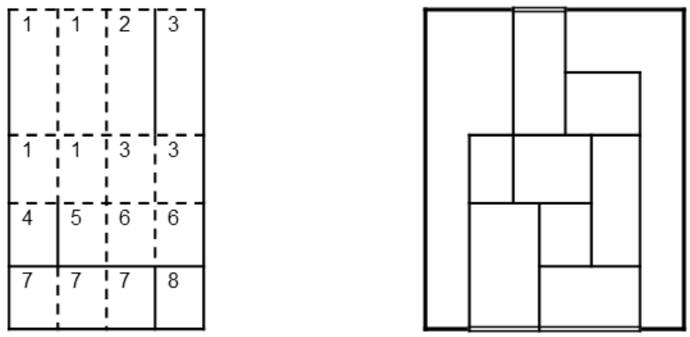


Figure 21, Discrete (left) and continual (right) layout representation

In a very general Quadratic Assignment Problem form, Kulturel-Konak (2007) generalize the DFLP and express it as follows by adopting the notation (except N, which represents the total number of departments and location, instead of n) used in Urban (1998):

Minimize

$$\sum_{t=1}^{T}\left[\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{N}\sum_{l=1}^{N} f_{ikt}d_{jl}x_{ijt}x_{klt} + \sum_{i=1}^{N} s_{it}y_{it} + r_t z_t\right]$$

Subject to

$$\sum_{i=1}^{N} x_{ijt} = 1 \qquad \forall j, t$$

$$\sum_{j=1}^{N} x_{ijt} = 1 \qquad \forall i, t$$

$$x_{ijt}, y_{it}, z_t \in \{0, 1\} \quad \forall i, j, t$$

Where f_{ikt} is the material flow between departments i and k in time period t, d_{jl} the distance between locations j and l, s_{it} the variable rearrangement cost of moving department i at the beginning of period t, , r_t the fixed rearrangement cost of performing any rearrangement at the beginning of period t. $x_{ijt}, y_{it}, and\ z_t$ are decision variables as follows:

$$x_{ijt} = \begin{cases} 1\ if\ department\ i\ is\ assigned\ to\ location\ j\ in\ period\ t \\ 0\ otherwise \end{cases}$$

$$y_{ij} = \begin{cases} 1\ if\ department\ i\ is\ relocated\ at\ the\ beginning\ of\ period\ t \\ 0\ otherwise \end{cases}$$

$$z_t = \begin{cases} 1\ if\ any\ rearrangement\ is\ amde\ at\ the\ beginning\ of\ period\ t \\ 0\ otherwise \end{cases}$$

The QAP formulation is a quite common way to represent the DFLP. The problem represented are related to equal size departments and must respect constraints ensuring that each location is assigned to one and only one departments at each period [20]. Budget constraints can be added in order to perform the reconfiguration of facilities on the floor plan, since the rearrangement cost must not exceed a certain level of budget. Moreover, the QAP formulation is not adequate to represent the exact position of facilities in the plant site and is not able to model properly specific constraints as the orientation, pick-up and drop-off points, or clearance between facilities.

Mixed Integer Programming formulation

In this case the layout representation is continual and all the facilities are positioned anywhere within the planar site, although they must not overlap each other's [10]. The facilities are located in the plant either by the position of their centroid coordinates (x_i, y_i), half length l_i and half width w_i or by the coordinates of bottoms left corner, length L_i and width W_i of the facility. If the distance between two departments is to be obtained, it can be , for example, expressed through the rectilinear norm [21]:

$$d_{ij}\left((x_i, y_i), (x_j, y_j)\right) = |x_i - x_j| + |y_i - y_j|$$

Since there always are area constraints on the plant site, it means that the total area available must be superior to the sum of all the facility areas.

A very important constraint is the non-overlapping of the facilities. Two conditions for the non-overlapping of the facilities are set by Welgama & Gibson (1993), X-projection non-overlapping and Y-projection non-overlapping condition:

$$(x_{jt} - x_{ib})(x_{jb} - x_{it}) \geq 0$$
$$(y_{jt} - y_{ib})(y_{jb} - y_{it}) \geq 0$$

Where (x_{it}, y_{it}) and (x_{ib}, y_{ib}) are the top left and the bottom right corners of the facility *i* and (x_{jt}, y_{jt}) and (x_{jb}, y_{jb}) are the top left and bottom right corners of the facility *j*. Resuming we can say that the layout optimization problem is expressed as follows:

Minimize the objective function

Subject to $A_{ij} \leq 0$

Where A_{ij} is defined as overlap area between two departments to formulate the constrain [23]. In this formulation the pick-up and drop-off points can be modelled as constraints in the layout problem formulation, meaning that the optimal position of P/D is treated as a specific problem. Other constraints are also treated, such as orientation of facilities and clearance between departments that can have constant value.

Graph-Theoretic Approaches

In this formulation of the layout problem, it is assumed that the desirability of locating each pair of facilities adjacent to each other is known, the area and the shape of each department is ignored (at the beginning), and each department is then represented by a node in a net. Satisfied adjacency between departments is represented by an arc that connects the two adjacent departments in the graph [24]. The objective function is:

$$max \sum_{i} \sum_{j} (r_{ij}) x_{ij}$$

Where x_{ij} equals 1 if departments *i* and *j* are adjacent, and 0 otherwise and r_{ij} is the closeness rate (numerical value that rates the closeness of department I with department j). This theory is based on the principle that material handling costs are reduced significantly when two departments are adjacent. The objective is creating a graph that maximizes the weights on the adjacencies (arcs) between departments pairs (nodes).

In order to develop a layout through a graph-theoretic approach Gau & Meller (1999) described that it is required to follow the these three steps:

1. Developing an adjacency graph from department relationship (which departments are adjacent).
2. Constructing dual graph of the adjacency graph (represent departments as adjacent regions having specific boundaries).
3. Converting dual graph into a block layout (specific layouts with regular shapes and specific areas).

The goal function of the graph-theoretical approach is maximized if all departments with positive interactions are connected through an arc. However, in order to facilitate the construction of the graph a limited number of arcs can be connected to each department, for this reason heuristics must be used to construct a maximally weighted adjacency graph. As previously discussed in the QAP approach, unequal-area problems of even small size cannot be solved optimally even with the graph-theoretical approach.

Solutions of the Problem

In this sub-chapter we will briefly discuss how the literature groups the various resolution approaches in the DFLP matter. Garey & Johnson (1983) demonstrated how facility layout problems are NP-hard, meaning that they have a degree of complexity that does not allow to find an optimal solution a part for very small size problems. The main class of methods that are to be discussed are the following:

- ***Exact methods***: first addressed by Rosenblatt (1986), a deterministic environment where input data and product demands are known for each period. In this family of methods, the main goal is to decide upon the layout for each period given the from-to flow matrices. Typical of this family are the QAP method and the graph-theoretic approach, the aim of these methods is reaching the optimal solution to the layout problem. In practice, it as been demonstrated that these kinds of problems are generally unsolvable to guarantee optimality.
- ***Heuristic***: where finding an optimal solution is impossible or impractical, heuristic methods can be used to speed up the process of finding a satisfactory solution. This family of methods is quite big and the evaluation of the applicability or performance of one heuristic over another can be subjective and dependent on several factors. The most common methods are adjacency-based algorithms (MATCH, SPIRAL etc.), distance-based algorithms (CRAFT, SHAPE, LOGIC and QLAARP) as well described by Gau & Meller (1999).
- ***Meta-heuristic***: many metaheuristic ideas were proposed to improve local search heuristic in order to find better solutions. Such metaheuristics include simulated annealing, tabu search, iterated local search, variable neighbourhood search, and GRASP. These metaheuristics can both be classified as local search-based or global search metaheuristics [18].
- ***Hybrid approaches***: this family of approaches has been recently addressed in the literature and it aims at proposing new hybrid algorithms based on already existing ones and results are quite interesting. As an example, Balakrishnan et al. (2003) developed a GA hybrid algorithm to overcome the problem related to the small size constraints on exact solution approaches.

As a matter of facts all these approaches have been of interest in the recent year, in particular the trend is moving towards meta-heuristic and hybrid approaches that can help when dealing with bigger size problems. Moreover, most of the past studies have dealt with greenfield problems while the FRLP (facility re-layout problem) is gaining more and more attention since manufacturing industries operate in highly volatile environment which motivate them to frequently redesign their layouts.

Stochastic Facility Layout Problems

This second approach of uncertainty treatment in the facility layout problem takes life from the assumption that product demand or product mix is not known deterministically but stochastically [7]. There is no single formulation for the stochastic FLP since different criteria are used as objectives. Two important notions have been used in literature to address this problem:

- ***Flexibility for future changes***: a flexible facility can be defined as a facility that can readily adapt to changes without significantly affecting performance.
- ***Robustness to uncertainty:*** a robust facility is one that behaves well over a variety of scenarios and outcomes.

As a matter of fact, having some vacant space in a layout could be a strategy to improve rapidity in change management and consequently increasing its flexibility, but this does not necessarily mean that the layout is also robust. In the following section main literature views are reported concerning these two notions in optimization of layout redesign.

Flexibility

Rosenblatt & Lee (1987) were among the first researchers to focus on the facility layout under uncertainty with focus on the concept of flexibility together with Tompkins in the 80'. They define flexibility as the ability of layouts to respond to current and future product mixes, then they present a methodology that quantifies flexibility by defining a facility penalty. This penalty is treated as a measure of effectiveness of the adaptability of several different layouts to the changing demand patterns of the products.

Another approach has been studied by Gupta (1986): in this case the use of simulation helps in solving FLP by considering the flexibility concept. Instead of assuming deterministic flows, he obtained the flow matrices by using Monte Carlo simulation to randomly generate flows between all pairs of departments. In Gupta's study squared shape and equal size department are used and individual flow volumes are assumed to be independent and normally distributed with known mean and standard deviation. Moreover, the CRAFT heuristic method is used to generate a layout for each flow matrix, then, for each layout, a distance-based cost function is calculated. Finally, the layout with the smallest penalty value is chosen as best option and as most flexible solution.

Bullignton and Webster (1987) proposed a way to evaluate the layout flexibility on the basis of a cost estimation of a future re-layout of the facility rather than on modification in the material handling costs. As a matter of facts, they distinguished between two types of flexibility: adaptive flexibility and reactive flexibility, the first is evaluated based on future re-layout, while the second based on material handling costs.

Kulturel-Konak (2004) consider product routing flexibility that results from modifications in the design or demand of products in the stochastic FLP. Therefore, routing flexibility can be considered as the ability to produce a part by alternative routes through the system.

Robustness

The first authors, to address the idea of *robustness* in a single period layout problem under stochastic demand, were Rosenblatt & Lee (1987). After they stated that finding an exact solution to the FLP is impractical, they suggested to model demand as a three-point random variable. Robustness can be defined as the frequency that a layout falls within a prespecified percentage of the optimal solution for different sets of production scenarios. Meaning that although a certain solution may not be optimal for a given scenario, it can be the most reliable for all the states.

Kouvelis et al. (1992) study upon single and multiple period layout problem can be seen as another step in the direction of facility layout problem under uncertainty to find a robust solution. They also used QAP formulation and they provided a systematic way to generate robust layouts for single and multiple period problems in uncertainty conditions. For what concerns multiple periods analysis it becomes more difficult to define robust layouts since relocation should be considered. In their study they distinguish the equipment that is difficult to be relocated and they call it *monument.* The systematic approach that they propose performs well in medium size problems and can be addressed as a heuristic for larger problems.

Benjaafar & Sheikhzadeh (2000) developed a study on FLP in stochastic environment, where in addition to variability of product mix and product demand, duplication of same department type may be allowed in the same plant. In fact, they have allowed the possibility of partial disaggregation, showing that duplication of the same department can significantly reduce material handling costs while effectively coping with fluctuations in volumes and flow patterns.

Azadivar & Wang (2000) approached the FLP problem by considering stochastic characteristics, such as interarrival times of parts of parts into the system and operational constraints of the system such as departmental area requirements. Their proposed approach integrates GA and computer simulation; therefore, this combination is capable of solving different layout problems.

Braglia et al. (2003) have assumed normally distributed product demand with expected values and variances. Through the help of simulation, they focus on finding the most robust layout. Although the proposed procedure has only been used on single row layout, Kulturel-Konak (2007) address how it could be interesting to apply it on a loop layout.

Finally, Kulturel-Konak (2004) has studied production uncertainty in block layout design with unequal area departments; however, product demands are not only independent and they can be correlated. Moreover, several classes of product demand forms are allowed and not only certain distributions. This study aims at optimizing all possible scenarios in the predefined continuous range by integrating the robustness function in between lower and upper bounds.

Chapter 4: Development of the Decision-making Method for Department Re-Layout Optimization

In the previous chapters, the discussion focused mostly on how, in the literature, the concept of lean manufacturing and continuous improvement has been addressed together with the facility layout problem. From the early years till today, the main research trends has been reported and compared. The ability to learn from the job floor experience and the philosophy of reducing all form of wastes has been reviewed and several interesting tools have been analysed. Moreover, the structured way of approaching the layout problem has been introduced both in static and dynamic form. What can be seen as an outcome of these literature review is that a great quantity of material and research effort is available concerning these topics, but most of the research does not find practical application in real case of study. The main objectives of this thesis are: in first place finding a good solution for the re-layout of a department inside a ceramic process factory and, in second place, giving to production analysts and engineers a structured approach to the continuous improvement problem when it coms to a re-layout analysis. This approach must go beyond the limits of *point kaizen* intervention, while at the same time, it should not abstract too much from the practical job-floor experience. Thanks to the union of SFLP theory and lean manufacturing principles, a set of alternative re-layout solutions are generated and, through the help of a simulation, tool are tested under diverse possible future scenarios.

Existing Layout Planning Procedures: Literature Overview

Several different procedures have been developed to help facility planners in choosing layout alternatives. These procedures can be categorized into two main groups: construction type and improvement type. *Construction* methods basically consists in generating layout alternatives "from scratch". *Improvement* procedures, instead, generate layout alternatives by seeking improvements in an existing layout, also defined as re-layout analysis. Although a quite big number of papers deal with the construction type problem, most practical layout works involve some form of improving the layout of a facility. We can refer to Immer's observation in the early 1950',

> *Much of the work will consist of making minor changes in existing layout, locating new machines, revising a section of the plant, and making occasional studies for material handling. The plans for a complete new production line or new factory may take the headlines, but except for a war or a new expansion, the average layout planner will very seldom have to consider such a problem.*

The observations made by Immer are still valid nowadays, even though the wide spread of lean manufacturing has led to a culture of change and continuous improvement that goes well beyond its definition of "minor changes". Moreover, new businesses are growing and spreading all over the world (especially in countries such as China, India) calling for the need of brand-new facilities and plant. It will now be introduced and discussed some of the original systematic approaches to the layout problem.

Apple's Plant Layout Procedure

Apple developed the following detailed sequence of steps in producing a plant layout:

1. Procure the basic data
2. Analyse the basic data
3. Design the productive process
4. Plan the material flow pattern
5. Consider the general material handling pattern
6. Calculate equipment requirements
7. Plan individual workstations
8. Select specific material handling equipment
9. Coordinate groups of related operations
10. Design activities interrelationships
11. Determine storage requirements
12. Plan service and auxiliary activities
13. Determine space requirements
14. Allocate activities to total space
15. Consider building types
16. Construct master layout
17. Evaluate, adjust, and check the layout with the appropriate persons
18. Obtain approvals
19. Install layout
20. Follow up on implementation of the layout

Apple's also stated that these steps are not necessarily to be addressed in the proposed sequence, since: "no two layout design projects are the same, neither are the procedures for designing them". He also describes how in his opinion there will always be a fair amount of jumping around and backtracking to previous steps to re-check or possible re-do a portion because of development that has not been foreseen.

Reed's Plant Layout Procedure

Another interesting procedure for the facility layout design has been suggested by Reed as a "Systematic Plan of Attack", in his study he recommended to follow these steps:

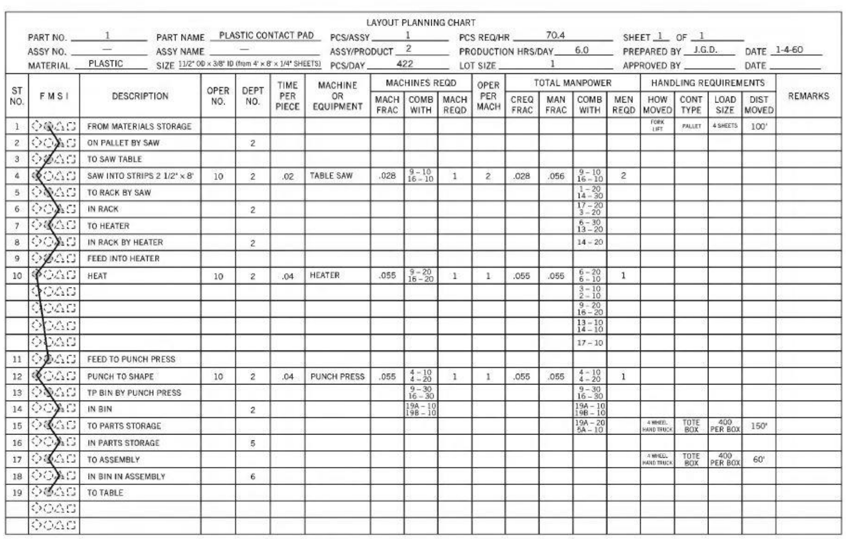
1. Analyse the product or products to be produced

2. Determine the process required to manufacture the product
3. Prepare layout planning charts
4. Determine workstations
5. Analise storage area requirements
6. Establish minimum aisles widths
7. Establish office requirements
8. Consider personnel facilities and services
9. Survey plants services
10. Provide for future expansion

Moreover, Reed describes the layout planning chart phase as "the most important single phase of the entire layout process" and he shows that it incorporates:

1. Flow process, including operations, transportation, storage and inspection
2. Standard times for each operation
3. Machine selection and balance
4. Manpower selection and balance
5. Material handling requirements

In Figure 22, Layout Planning ChartFigure 22 an example of a layout planning chart is provided. This chart can be seen as a predecessor of the value stream mapping tool used nowadays in lean manufacturing as already explained in previous chapter at page 27.


LAYOUT PLANNING CHART

PART NO. 1 — PART NAME PLASTIC CONTACT PAD — PCS/ASSY 1 — PCS REQ/HR 70.4 — SHEET 1 OF 1
ASSY NO. — — ASSY NAME — — ASSY/PRODUCT 2 — PRODUCTION HRS/DAY 6.0 — PREPARED BY J.G.D. — DATE 1-4-60
MATERIAL PLASTIC — SIZE 11/2" OD × 3/8" ID (from 4' × 8' × 1/4" SHEETS) — PCS/DAY 422 — LOT SIZE 1 — APPROVED BY — DATE

ST NO.	F M S I	DESCRIPTION	OPER NO.	DEPT NO.	TIME PER PIECE	MACHINE OR EQUIPMENT	MACHINES REQD: MACH FRAC	MACHINES REQD: COMB WITH	MACHINES REQD: MACH REQD	OPER PER MACH	TOTAL MANPOWER: CREQ FRAC	TOTAL MANPOWER: MAN FRAC	TOTAL MANPOWER: COMB WITH	TOTAL MANPOWER: MEN REQD	HANDLING REQUIREMENTS: HOW MOVED	HANDLING REQUIREMENTS: CONT TYPE	HANDLING REQUIREMENTS: LOAD SIZE	HANDLING REQUIREMENTS: DIST MOVED	REMARKS
1		FROM MATERIALS STORAGE													FORK LIFT	PALLET	4 SHEETS	100'	
2		ON PALLET BY SAW		2															
3		TO SAW TABLE																	
4		SAW INTO STRIPS 2 1/2" × 8'	10	2	.02	TABLE SAW	.028	9 – 10 16 – 10	1	2	.028	.056	9 – 10 16 – 10	2					
5		TO RACK BY SAW											1 – 20 14 – 30						
6		IN RACK		2									17 – 20 3 – 20						
7		TO HEATER											6 – 30 13 – 20						
8		IN RACK BY HEATER		2									14 – 20						
9		FEED INTO HEATER																	
10		HEAT	10	2	.04	HEATER	.055	9 – 20 16 – 20	1	1	.055	.055	6 – 20 6 – 10	1					
													3 – 10 2 – 10						
													9 – 20 16 – 20						
													13 – 10 14 – 10						
													17 – 10						
11		FEED TO PUNCH PRESS																	
12		PUNCH TO SHAPE	10	2	.04	PUNCH PRESS	.055	4 – 10 4 – 20	1	1	.055	.055	4 – 10 4 – 20	1					
13		TP BIN BY PUNCH PRESS						9 – 30 16 – 30					9 – 30 16 – 30						
14		IN BIN		2				19A – 10 19B – 10					19A – 10 19B – 10						
15		TO PARTS STORAGE											19A – 20 5A – 10		4 WHEEL HAND TRUCK	TOTE BOX	400 PER BOX	150'	
16		IN PARTS STORAGE		5															
17		TO ASSEMBLY													4 WHEEL HAND TRUCK	TOTE BOX	400 PER BOX	60'	
18		IN BIN IN ASSEMBLY		6															
19		TO TABLE																	

Figure 22, Layout Planning Chart

Muther's Systematic Layout Planning (SLP) Procedure

In the early year of 1970' Muther developed a procedure for the facility layout design named *Systematic Layout Planning (SLP).* A picture concerning the structure of the framework can be observed in **Error! Reference source not found.**, this framework uses the activity relationship d iagram as its base and starting from the input data and understanding of the roles and relationships between each activity, a *from-to chart* and an *activity relationship chart* are developed. When the analysis phase is completed a *relationship diagram* is drawn as can be seen in Figure 24.

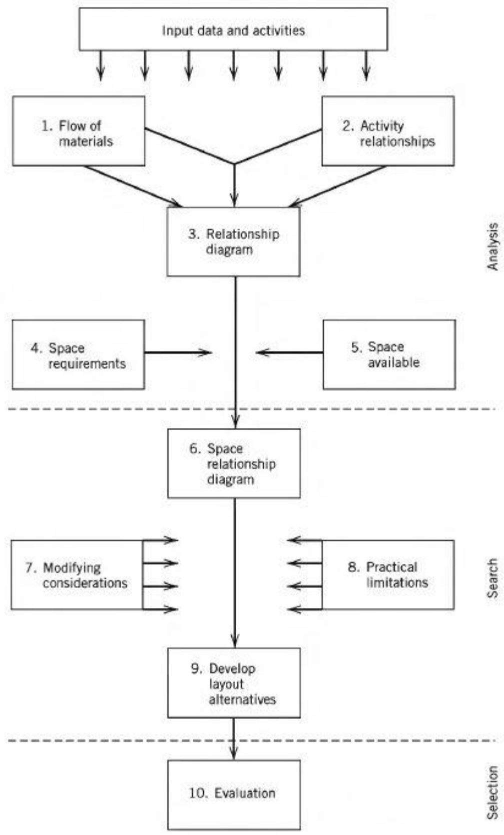


Figure 23, Systematic Layout Planning (SLP) Procedure

The relationship diagram positions activities spatially and proximities are generally used to represent the relationship between couples of activities. The following two steps include the determination of the amount of space to be assigned to each activity. Once the space assignment has been developed, space templates are built for each planning department or facility and the space is "hung at on the relationship diagram" to obtain what is called *space relationship diagram* (Figure 25).

Finally, based on practical constraints of the real problem and objective limitations, a number of layout alternatives are developed and then evaluated. In conclusion the procedure identifies one preferred alternative. The SLP procedure can be used sequentially for the development of first a block layout and then a detailed layout for each department. In the latter case, relationships between workstations, machines and input/output locations are used to determine relative location activities inside each department.

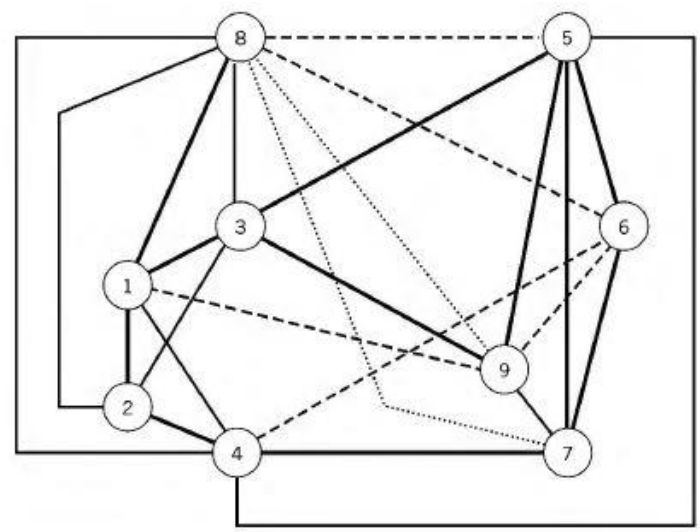


Figure 24, Relationship Diagram

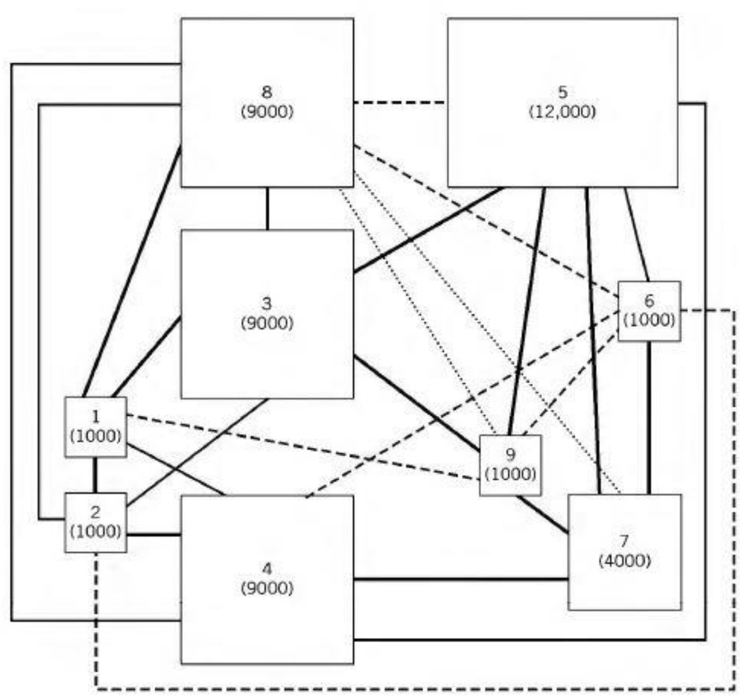


Figure 25, Space Relationship Diagram

The Method

In this section the core of the thesis project will be developed and clarified. It will be introduced for the first time a framework to be followed by managers and facility planners when approaching the re-layout design (improvement condition) of a production or material storage department. The methodology aims at combining a *static* and a *dynamic* factory layout planning approach.

Moreover, as shown in Figure 26 the first step in the procedure evolves with three main parallel routes: The *Lean Approach*, the *Muther's Systematic Layout Procedure,* and the *Combinatorial Search Procedure.* As a matter of fact, each of these procedures entails a different vision and approach:

- ***Lean Approach***: The purpose of this procedure is to allow the facility planner to experience the job-floor and understand deeply the department routines. This phase is based on the lean philosophy of identifying and eliminating the source of waste, with the aim of optimizing the operations. Basically, the process begins with the observation of events happening on daily base and on different shifts, so that the manager can get a good understating of the main issues. The *chalk circle* approach consists of sitting still in the department for hours or even entire shifts in order to collect information regarding all the wastes and problems in the department, learn by watching. Once the situation is clearer the next step is walking around the department (*Gemba walk*) watching every single detail of the daily operation routine, at the same time a broader understating of the process can be achieved through data collection in neighbour departments. After having achieved a deep understanding of the operations development, the manager should use an interesting tool that has been defined at page 31 called *Spaghetti Diagram*. This tool helps in understanding the recurrent movement of the operators in the job floor during their daily work. Together with the *Value Stream Mapping Tool*, that is fundamental to classify which operations are truly adding value to the final product, these tools allow to understand which operations are only a waste of time and resources. Finally, the 5S tool previously described in the **Lean Manufacturing Tools and Layout Design Improvement** chapter will be used to suggest improvement and standardization of the production process.
- ***Muther's Systematic Layout Planning Procedure***: This second parallel phase, of what has been addressed as the *static facility layout planning,* has just been described in the previous chapter and represent a graph based method to achieve new layout alternative that can reduce a predetermined cost function. Once all the steps in the systematic layout planning procedure have been followed the manager will have a useful space-relationship diagram that will guide him in generating some layout alternatives and later he will have to choose the best one between them based on the specific cost function chosen.
- ***Combinatorial Search Procedure***: This third and last parallel phase to be developed by the manager is more numerical oriented then the first two. As a matter of fact, the manager will have to use the aid of a computer system to develop the big amount of computational effort. In this thesis project a specific Excel add-in for the facility layout planning has been installed: it allows to rapidly evaluate the overall cost function of a suggested layout and, moreover, allows to develop a combinatorial search process. The add in work by first generating a random sequential layout worksheet and based on the input data previously updated (flow matrix, cost matrix, department data etc.) and then the *Optimize* add-in generates 10 random permutations and the *Layout* add-in evaluates them. The best of the

10 are placed on the combinatorial form. The program continues in the search for the optimum by starting from the best random result and choosing the improvement option that tries all 2 and 3-change variations of the layout. The process first tries all 2-change variations and whenever a change results an improvement, the two permutation positions are switched in value. The process continues until no 2-change switch results in improvement, then all 3-change switches are evaluated. The program terminates when a complete run through the changes results in no improvement. The layout measure has been improved, but there is no guarantee that the solution is optimal. Finally, with this new information the manager will have a more abstract solution, but much more optimized then the other solutions previously obtained. This will help him in understanding which layout and workstation allocation in the department would ideally reduce the cost function (almost) at best.

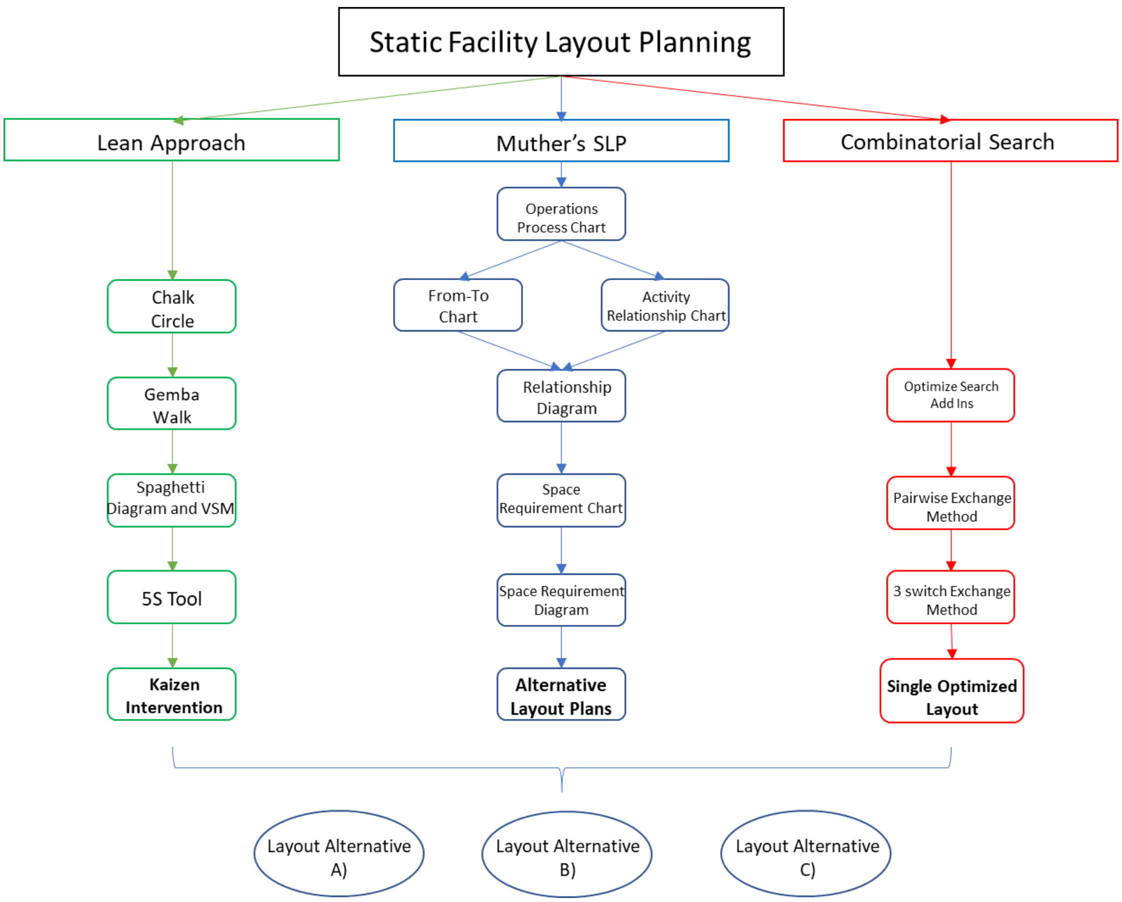


Figure 26, Static Facility Layout Planning

Once all the three paths have been developed, the manager or facility planner will have a deep and broad vision of the operational and structural improvement that could be done to achieve the best trade-off improvement solution. As a matter of fact, the next step in the decision-making process is the generation of realistic layout alternatives based on the three outputs of the previously described paths. The suggesting is, as shown in Figure 26, the generation of at least 3 alternatives that will have to be tested in the next step of the decision-making process.

The second step of the process concerns the testing of the solutions both on a qualitative (Figure 27) and quantitative way (Figure 28). The qualitative testing of the three proposed alternatives is developed in the form of a questionnaire (see Appendix 1) where the main figures in the plant's production management are asked to grade six key parameters from 1-5 based on their experience in the field. This will help in keeping the practical sense of the work of re-designing the layout in a department without loosing the objective of satisfying the main stockholders involved in the project. Thus, due to the well-known principle that the success of a project doesn't only depend on the technical outcome of the chosen solution. As a matter of fact, a major part of the success depends on the stockholder's satisfaction and their direct or indirect involvement during the whole process.

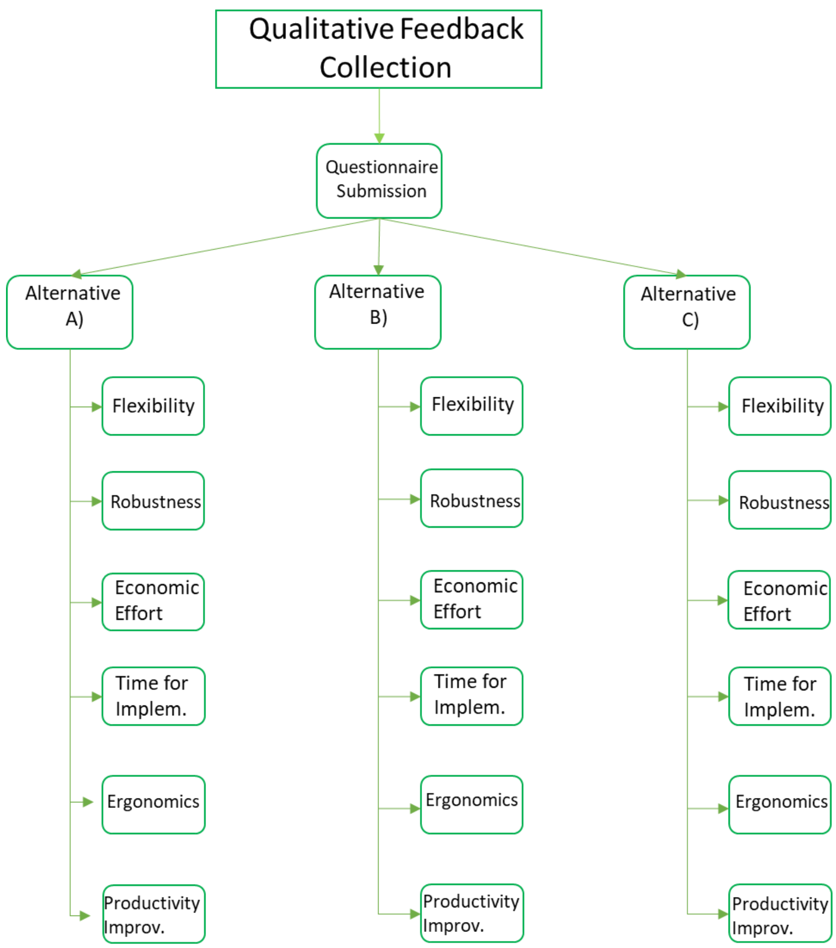


Figure 27, Qualitative Testing Process

The scores achieved can be summed based on the relevance (weight) of each key parameter and a final rank can be made based on the highest score. The solution that achieves the highest score will be the one with the best approval from the management of the factory.

The next step in the decision-making process, after having generated and qualitatively tested the three alternatives, brings inspiration from the *dynamic facility layout planning* problem that we addressed at Page 35. This step aims at quantitatively testing each solution on different levels. Thanks to the simulation software AutoMod, a detailed model of each alternative layout is programmed with specific forecasts on how the operational improvement will be, both in terms of cycle times and resource utilization. Once the three models have been verified and validated, an As-Is situation is tested at different speed levels (increasing the push or flow throughput), starting with a *low*, then *medium* and finally *high* level of speed to understand how each new solution behaves with respect to the original one while keeping the same Pmix composition. After that, a series of diverse future scenarios are generated based on possible future change in the product mix and each one of them is tested at regime conditions with a gradual contraction and expansion of the changes.

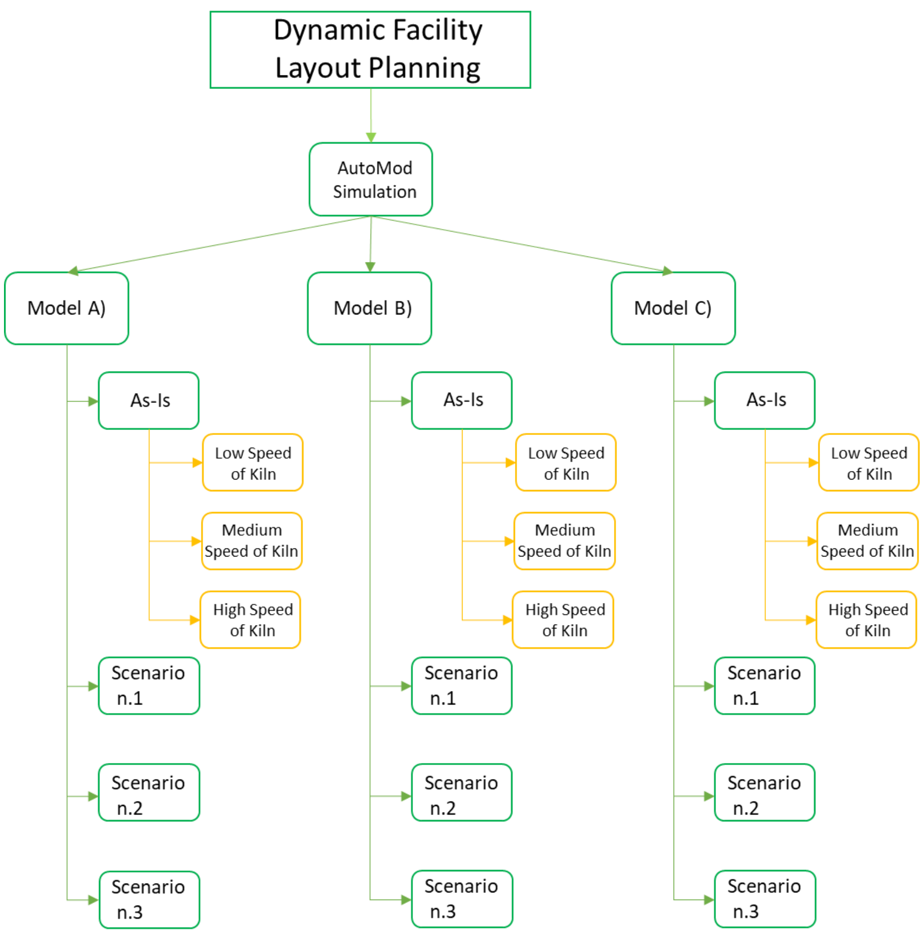


Figure 28, Quantitative Testing Process

Finally, after having tested all the conditions and compared them, a ranking between the three solutions is made based on their robustness, productivity performance and amount of generated work in progress. At the end of the decision-making process, the manager or facility planner will be able to justify a re-design solution of an already existing facility both from a static and a dynamic point of view, together with a qualitative feedback of the plants management. He will produce a robust solution to future changes, and efficiently improved in the current asset, while keeping attention to the main stakeholders of the project to guarantee its success. All of that with the aim of improving the quality of work and ergonomics of the operations in the job-floor, for a sustainable production process.

Chapter 5: The Ceramic Process Industry Case Study

In the previous chapters "2-3" the literature has been reviewed for what concerns the lean manufacturing philosophy and the facility layout problem. Several tools and procedures have been addressed to better understand what is needed for approaching a layout and operational improvement process. Moreover, in chapter 4 a decision-making process has been suggested in order to help managers when dealing with a re-layout problem, addressing this issue from both a static and dynamic point of view. Finally, in this chapter, a real case study will be presented where all the steps of the decision-making process will be followed, and the outcome presented. Most of the relevant details concerning the project and the boundary condition of the case study have already been addressed in the introductory chapter, but it is worth to be reminded that the plant works as a ceramic discrete process where a continuous flow should be kept 24 hours a day for 7 days a week and the department involved is the inspection and packaging department outside the kiln that must withstand a high product variety and logistics complexity.

Static Facility Layout Planning

It this first section the three parallel routes, described in the previous chapter, will be put in practice and the final outcome of each one of them will be used to integrate the knowledge acquired and to propose the three concrete layout alternatives.

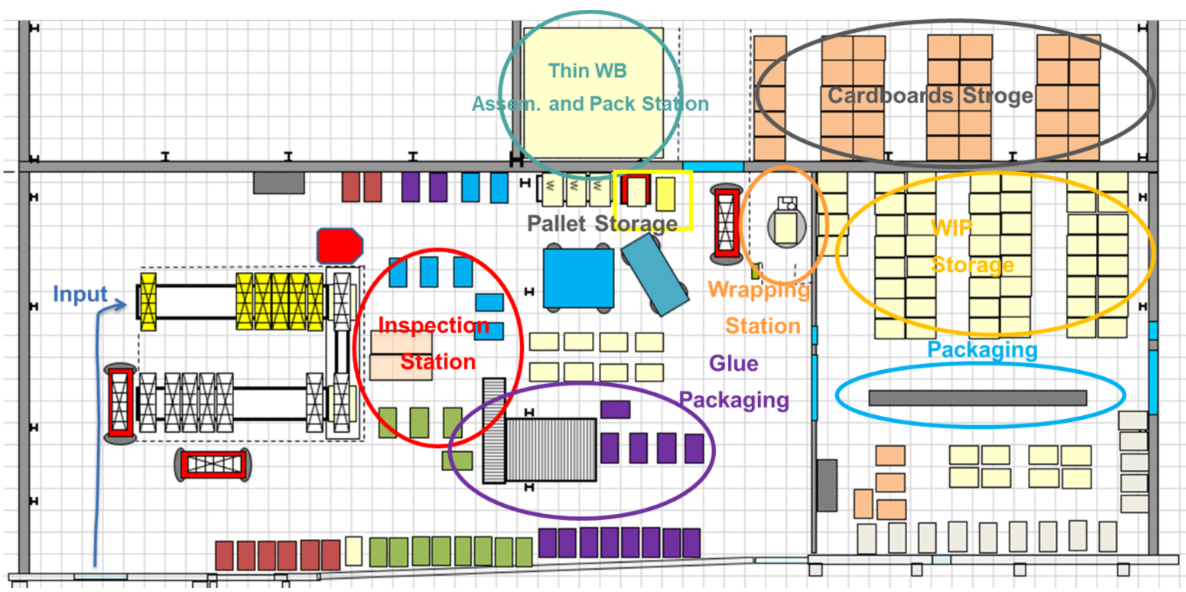


Figure 29, Current FFC inspection and packaging layout

Lean Approach

This first branch of the process is the most "practical" and the solutions that will be achieved are the most "experience-based" with respect to the other two branches. The idea is "understanding by doing" and watching and gaining confidence and knowledge of the current asset. In this phase a good amount of time as been spent observing the process and participating to the operations.

Chalk Circle and Gemba Walk in the FFC Department

As resumed at page 26 this phase is one of the most time consuming, since during this phase the factory planner must stand still inside the department, possibly in a location with a good view and he must collect information regarding the operations and layout composition. Moreover, he must walk around the department and neighbour areas to collect useful links and details for the further analysis.

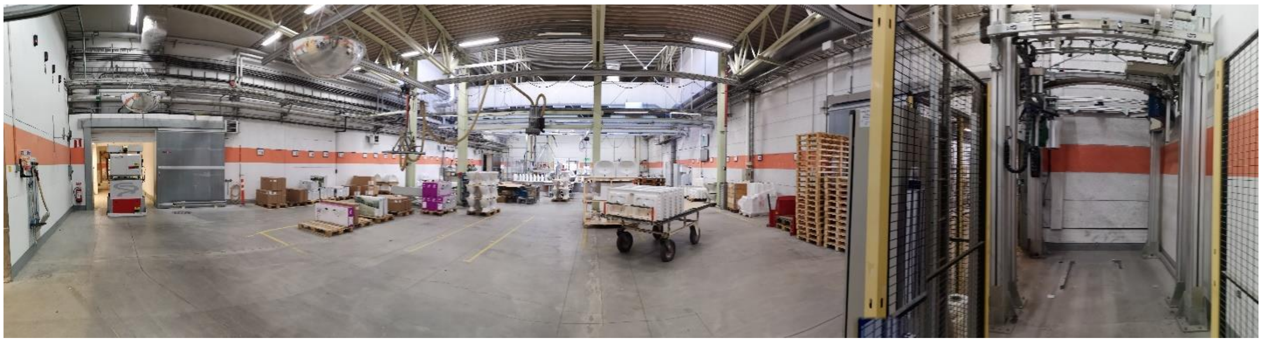


Figure 30, Complete view of FFC department

Below there is a list of the main information that has been gathered during this phase:

- *High quantity of work in progress*: there are several half full pallets all over the inspection area and they occupy a great amount of space.

Figure 31, pallet waiting to be filled in the FFC department

- *Low standardization of operation*: operator spend most of the time doing non-standardized operations from material handling up to pallet transportation, only small amount of operations is actually standardized.
- *High logistic complexity*: due to the high product variety it is notable that one of the two operator spends almost all its time walking around the department moving material.
- *Low ergonomics*: especially for what concerns the packaging of the FFC models the operators are subjected to repetitive lifting of heavy washbasins without any tool aid. Moreover, thy must walk a high number of steps that is not adding value to the process.
- *Unclear communication between departments*: it appeared that part of the complexity in the operational process developed due to lack of clear communication and information exchange between the casting, glazing and inspection area.
- *High Pmix Variety*: due to the fact that kiln 21 is currently use to fire floor standing bowls, wall hanging bowls, vitro china washbasins, fire fine clay washbasins and even for re-firing some repaired pieces, the inspection department is subjected to a very high product variety that complicates the flow.

Value Stream Mapping and Spaghetti Diagram

After having observed the process from close distance, two more tools have been used to specifically address the waste identification process. Firstly, a macroscopic overview of the production flow has been developed and the non-value activities have been identified. The value stream mapping tool must be used in order to comprehend where value is generated throughout the production process: in Figure 32 you can see how the process develops from raw material to finished products.

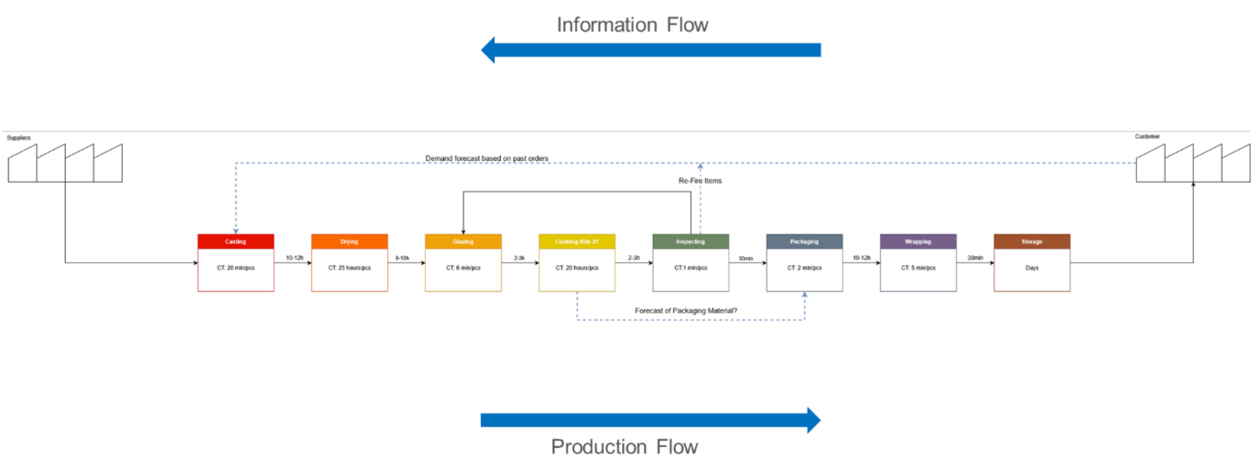


Figure 32, VSM of plant's production process

Out of the VSM of the process we can understand that, although really automated, the plant is not as lean as it could appear at first sight. As a matter of fact, also due to the nature of the ceramic process, there are high number of non-value adding activities and an overall high amount of work in progress in between production steps (products can wait days in between production steps).

In second place, by keeping track of the movements of each operator during the daily working routine, a spaghetti diagram for each product type has been produced, as shown in Figure 33, Example of a spaghetti diagram for floor standing bowls inspection.

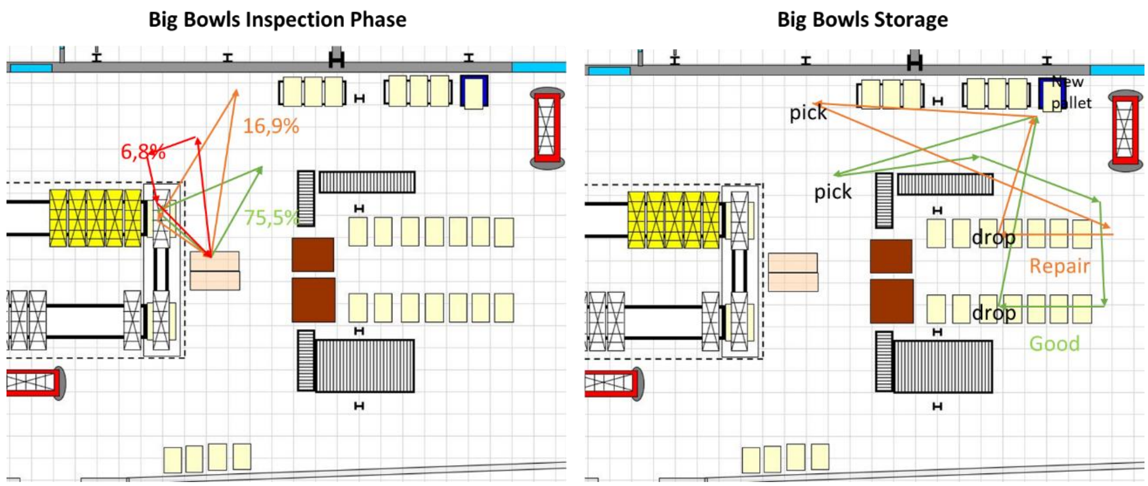


Figure 33, Example of a spaghetti diagram for floor standing bowls inspection and storage

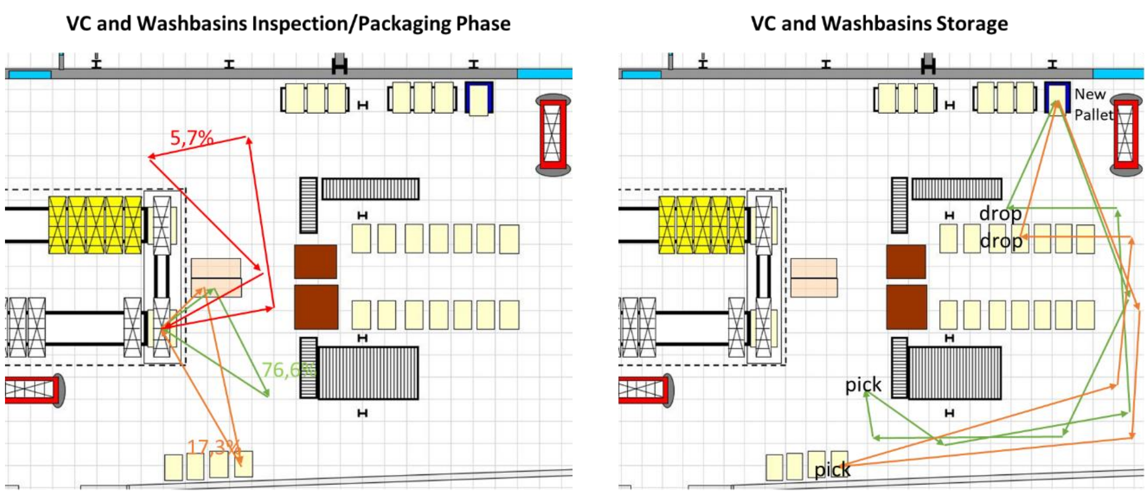


Figure 34, Example of a spaghetti diagram for VC and washbasins inspection & storage

Several of those graphs have been developed to better understand the movements of each operator and how to optimize them later on.

Once all the movement were clear and the value through out the chain was addressed, the possible action, to be taken to pursue kaizen improvement, have been discussed.

5S tool application and suggestion of Kaizen intervention

By applying the 5S rules of *sort*, *stabilize*, *shine*, *standardize* and *sustain*, the facility planner can reorganize the department so to reduce waste and increase inspection and packaging quality outputs. In this case study, by applying the 5S tool in the FFC department, some main improvement suggestions arise:

1. Reorganize space by removing gluing station from central area (sorting)

2. Improve information exchange through a forecast of the next FFC models to be inspected (stabilize)
3. Optimize the flow by performing FFC packaging directly after inspection phase (one touch rule and single piece process flow)
4. Separate the flow between bowls and washbasins after inspection (standardize)
5. Improve ergonomics by introducing a new lifting tool (sustain)

Muther's Systematic Layout Planning

In this second branch of the *static facility layout planning*, the already introduced Muther's approach has been used to get some alternative possible improvement solutions , focusing mainly on the workstation's allocation in the available space.

This procedure, professed by Richard Muther, makes use of the following tools:

1. Operation process chart
2. From-to chart
3. Activity relationship chart (ARC)
4. Relationship diagram
5. Space requirement chart
6. Space requirement diagram
7. Alternative layout plans
8. Modifying considerations
9. Selected layout plan

For sake of computational effort, a number equal to 10 department has been chosen to describe the current asset of the FFC inspection and packaging department (Figure 35).

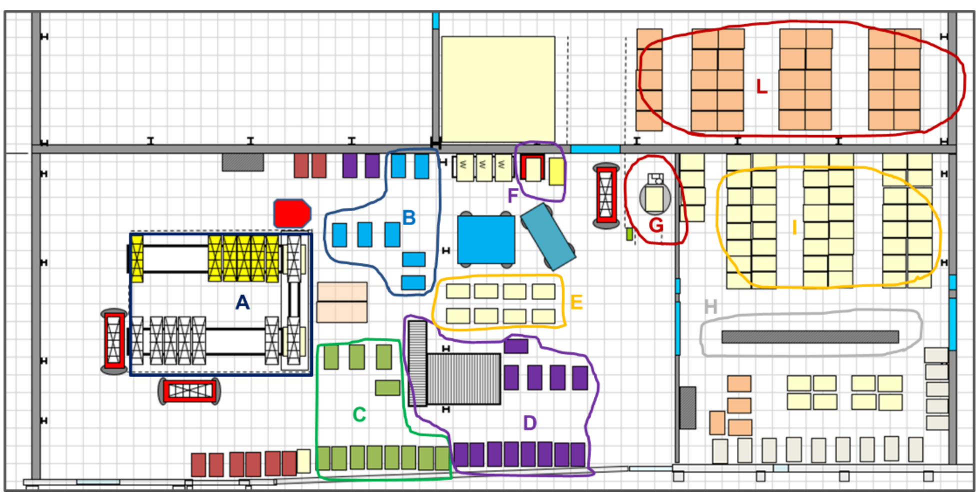


Figure 35, Current layout subdivision

Step 1: Operation process chart

The development of a process activity chart helps in understanding the sequence and nature of activities that each product performs inside the department. For each product type the precise sequence of operations, needed to complete the cycle time, has been reported, as shown in Table 3. The span of time spent by each operation has been estimated and reported together with the correct sequence.

Table 3, Operation Process Chart (floor standing bowls)

#	ACTIVITY	TIME	Sequence	WORK	MOVEMENT	TRANSPORT	WAITING	INSPECTION
1	AGV loads full KC on buffer	00:02:30	A					
2	KC queues onto conveyor	00:24:30	A					
3	Operator picks bowl from KC	00:00:05	B					
4	Operator inspect the bowl	00:00:35	B					
5	Operator moves bowl on pallet/waste	00:00:20	B					
6	Operator press button to update result	00:00:05	B					
7	Operator press button to switch KC	00:00:10	B					
8	Bowls wait on pallet untill full	00:20:00	B					
9	Operator moves full pallet in terget position	00:04:00	E					
10	AGVs brings pallet away							

Step 2: From-to chart

Also called a travel chart, a from-to chart is a tabular record of the movement of materials among departments and activities in quantitative units. Since different product have different sizes and weights, they cannot be treated as if they where all the same. For this reason, in order to evaluate a from-to flow matrix, we need to parametrize and scale each piece based on its weight and bulkiness. For this reason, an equivalent flow is evaluated taking as standard scale the weight and bulkiness of a bowl and reparametrizing all the other pieces. All the data used have been calculated based on historical data of standard production rate of kiln 21.

Table 4, Calculation of the equivalent flow

Step 2.a : Calculation of the equivalent flow within the department

Class	Volume	Weight	Production Quantites (pcs/day)	Movement Factor	Equivalent Flow (pcs/day)	Routing
Bowls	**35829**	**59.06%**	**561.0**	1	561	A-B-E
FFC Pack	**10483**	**17.28%**	**164.0**	3.5	574	A-B-H-I-G
VC Washbasin	**6046**	**9.97%**	**94.0**	2.5	235	A-C-E
Hangwall Bowls	**4450**	**7.34%**	**69.0**	1	69	A-C-E
FFC Glue	**3857**	**6.36%**	**60.0**	3	180	A-C-D-G
Cardboard Pack			164.0	0.33	54	L-H
Cardboard Glue			60.0	0.33	20	L-D
Bowl's Pallet			46.0	1.5	69	F-B
Wallhang Bowl's Pallet			5.0	1.5	8	F-C
VC's Pallet			5.0	1.5	8	F-C
FFC's Pallet			16.0	1.5	24	F-I
FFC Glue's Pallet			7.0	1.5	11	F-D
Cardboard VC			20.0	0.33	7	
Skivan			97.0	1	97	
Compressed Chips board			5.0	1	5	

Last 4 months inspected pcs out of K21

Routing of each object inside the department

Production Quantities x Movement Factor

Once the equivalent flow has been calculated the from-to matrix can be constructed as shown in Table 5. Basically, it is necessary to sum up for each cell the contribution in pcs/day that flows in the associated direction

Table 5, From-To Matrix

Step 2.b :Flow matrix construction

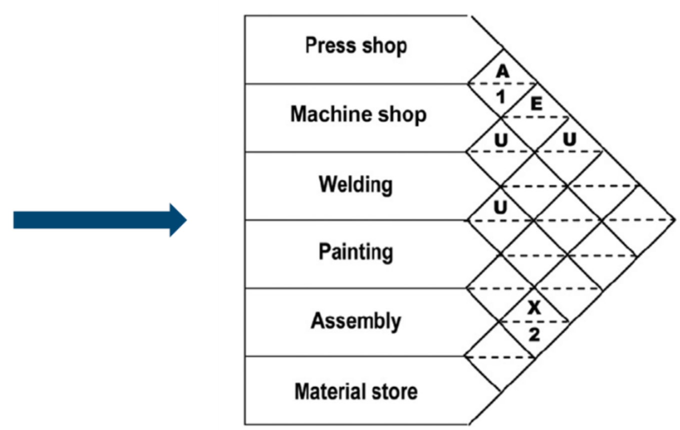
Material Flow Matrix										
From/To	A	B	C	D	E	F	G	H	I	L
A		1135	484	0	0	0	0	0	0	0
B	0		0	0	561	0	0	574	0	0
C	0	0		180	304	0	0	0	0	0
D	0	0	0		0	0	180	0	0	0
E	0	0	0	0		0	0	0	0	0
F	0	69	15	10.5	0		0	0	24	0
G	0	0	0	0	0	0		0	0	0
H	0	0	0	0	0	0	0		574	0
I	0	0	0	0	0	0	574	0		0
L	0	0	0	19.8	0	0	0	54.12	0	

Step 3: Activity relationship chart

An ARC indicates in tabular format the closeness rating among all pairs of activities or departments in a shop that are considered for planning an industrial layout. In an ARC, there are six closeness ratings, as indicated below, which may be assigned to each pair of departments, as shown in Table 6.

Table 6, Activity relationship chart

- » A Absolutely necessary — $w_A = 20$
- » E Especially important — $w_E = 10$
- » I Important — $w_I = 5$
- » O Ordinary — $w_O = 2$
- » U Unimportant — $w_U = 0$
- » X Undesiderable — $w_X = -10$



Based on the affinities between areas/workstations inside the department the symmetric matrix in Table 7 is constructed.

Table 7, Relationship-based matrix

Relationship-based Matrix										
From/To	A	B	C	D	E	F	G	H	I	L
A		20	20	0	0	0	0	5	0	0
B			2	0	10	10	0	10	0	0
C				5	10	10	0	0	0	0
D					0	5	5	0	0	10
E						10	0	0	0	0
F							2	2	10	2
G								5	2	0
H									5	10
I										2
L										

Step 4: Relationship Diagram step by step

1) Choose the two departments that shares higher affinity values:

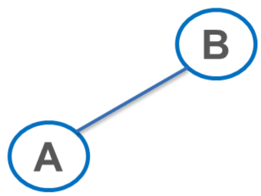


Figure 36, Step 1)

2) Choose a 3rd department that scores highest affinity with the previous two:

	A	B	TOT
C	20	2	22
D	0	0	0
E	0	10	10
F	0	10	10
G	0	0	0
H	5	10	15
I	0	0	0
L	0	0	0

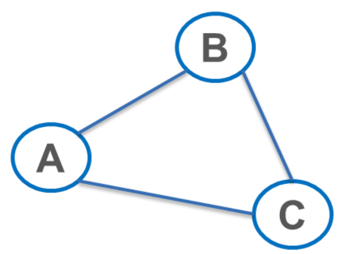


Figure 37, Step 2)

3) Choose a 4th department that scores highest affinity with the previous three:

	A	B	C	TOT
D	0	0	5	5
E	0	10	10	20
F	0	10	10	20
G	0	0	0	0
H	5	10	0	15
I	0	0	0	0
L	0	0	0	0

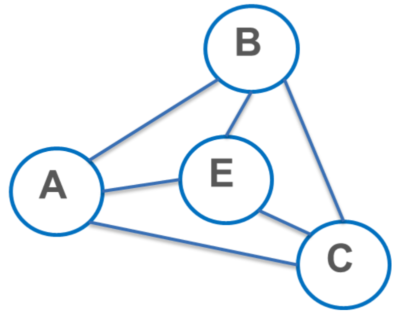


Figure 38, Step 3)

4) Choose a 5th department that scores highest affinity with the previous and locate it inside the arc that maximize the affinity level:

	A	B	C	E	TOT
D	0	0	5	0	5
F	0	10	10	10	30
G	0	0	0	0	0
H	5	10	0	0	15
I	0	0	0	0	0
L	0	0	0	0	0

Faces	TOT
ABE	20
ACE	20
EBC	30

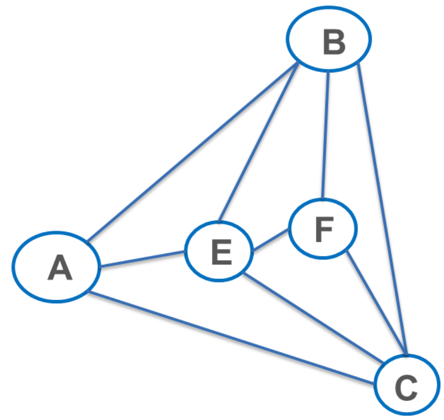


Figure 39, Step 4)

5) Choose a 6th department that scores highest affinity with the previous and locate it inside the arc that maximize the affinity level:

	A	B	C	E	F	TOT
D	0	0	5	0	5	10
G	0	0	0	0	2	2
H	5	10	0	0	2	17
I	0	0	0	0	10	10
L	0	0	0	0	2	2

Faces	TOT
ABE	15
BEF	12
BFC	10
EFC	2
AEC	0

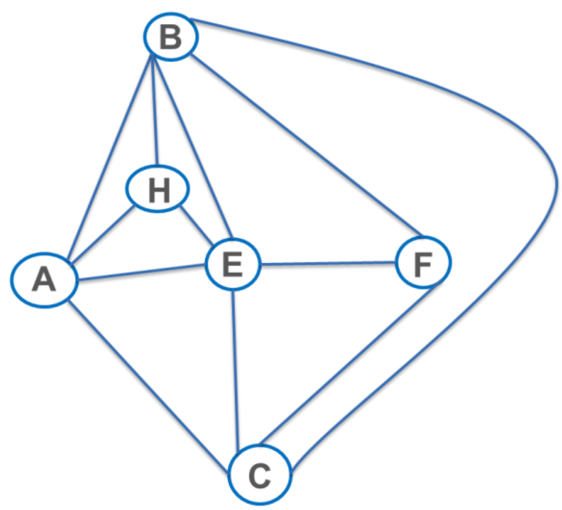


Figure 40, Step 5)

6) Choose a 7th department that scores highest affinity with the previous and locate it inside the arc that maximize the affinity level:

	A	B	C	E	F	H	TOT
D	0	0	5	0	5	0	10
G	0	0	0	0	2	5	7
I	0	0	0	0	10	5	15
L	0	0	0	0	2	10	12

Faces	TOT
FEC	10
BEF	10
BFC	10
AHB	5
AHE	5

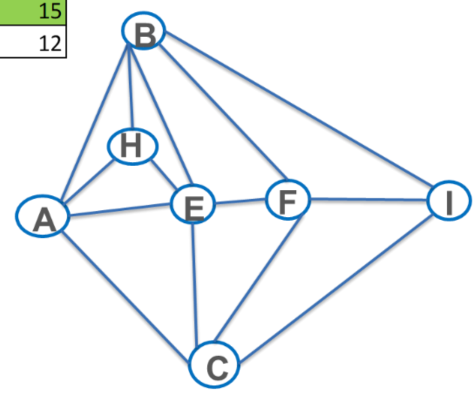


Figure 41, Step 6)

7) Choose an 8th department that scores highest affinity with the previous and locate it inside the arc that maximize the affinity level:

	A	B	C	E	F	H	I	TOT
D	0	0	5	0	5	0	0	10
G	0	0	0	0	2	5	2	9
L	0	0	0	0	2	10	2	14

Faces	TOT
BHE	10
AHE	10
AHB	10
BEF	2
EFC	2

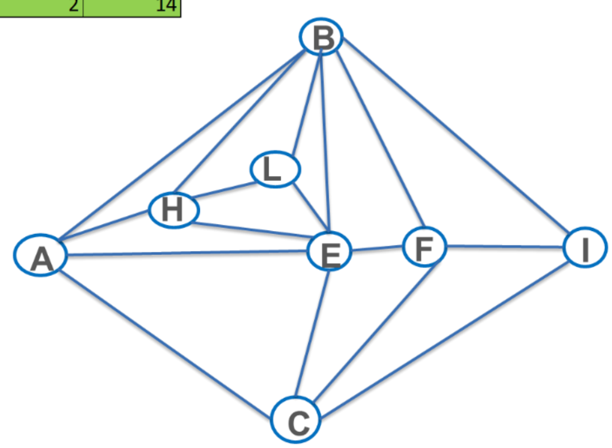


Figure 42, Step 7)

8) Choose a 9th department that scores highest affinity with the previous and locate it inside the arc that maximize the affinity level:

	A	B	C	E	F	H	I	L	TOT
D	0	0	5	0	5	0	0	10	20
G	0	0	0	0	2	5	2	0	9

Faces	LBE	FEC	BLH	LHE	FBI	FCI	FBE
TOT	10	10	10	10	5	10	5

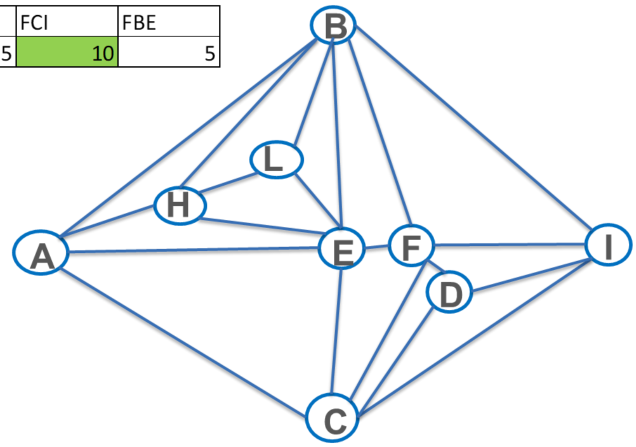


Figure 43, Step 8)

9) Choose the 10th and last department so that it scores highest affinity with the previous and locate it inside the arc that maximize the affinity level:

	A	B	C	E	F	H	I	L	D	TOT
G	0	0	0	0	2	5	2	0	5	14

Faces	FDI	BFI	DIC	FBE
TOT	9	4	7	2

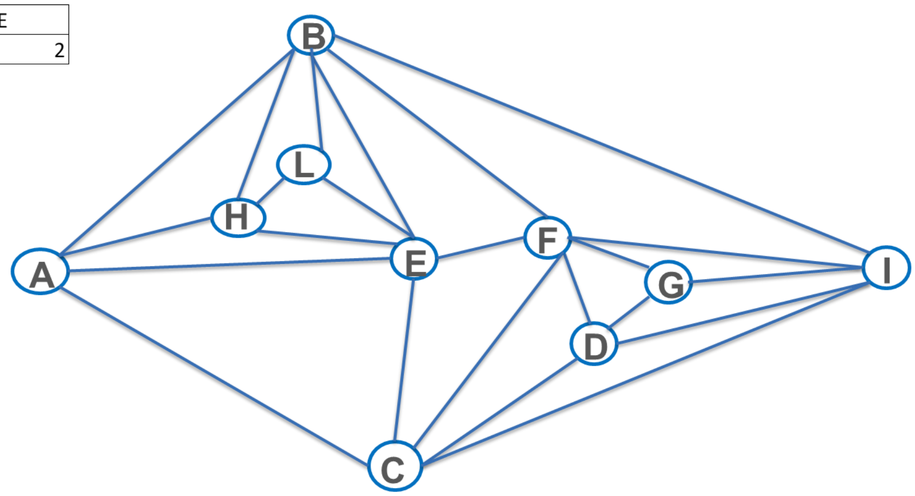


Figure 44, Step 9)

Finally, a complete net of how relationship could be connected is completed. Starting from this net, other constraints will be introduced such as space and building size. Of course, the composition of the net depends on the first two department chosen at the beginning and by repeating the same procedure with different starting departments the final solution will be different every time. As a matter of facts, each solution will bring a margin for improvement also if no optimal solution is achievable through this graph-based approach.

Step 5 and 6: Space requirement chart and diagram

Once the relationship diagram is drawn the next step involves the space constraint evaluation. In a space requirement chart (Table 8), each department is tabulated with respect to the area required in square meters and the need for any other special provisions needed.

Table 8, Space Requirement Chart

Department	Required ares in squared meters
A	108
B	32
C	44
D	54
E	14
F	4
G	18
H	33
I	128
L	114

In the space requirement diagram (Figure 45, Space Requirement Diagram) the relationship diagram is displayed based on the area constraints.

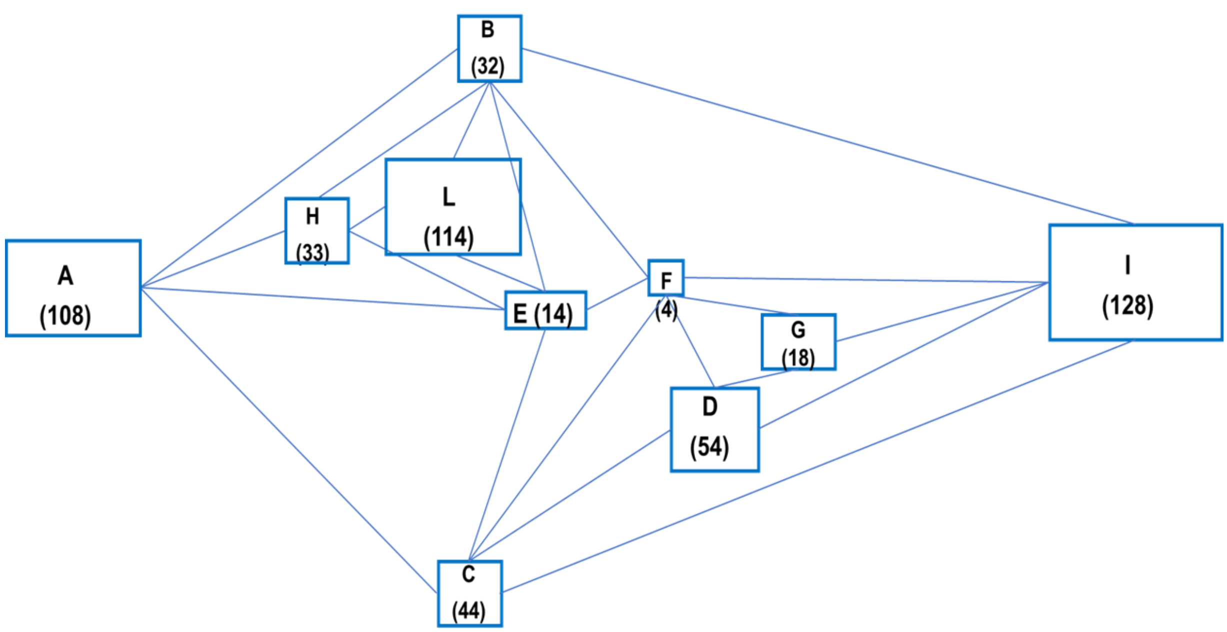


Figure 45, Space Requirement Diagram

Step 7: Alternative Layout Generation

Once the space relationship diagram is known we have a better understanding of which departments should be closer to each other. Based on this, we can draw a tentative initial layout plan. In a similar manner, we may develop three or four alternative plans considering all the pros and cons.

Before proposing the new alternative, it is convenient to evaluate the original configuration through a cost function the works as follow:

Cost of internal transportation

$Q_{ij} = total\ material\ flow\ in\ departments\ \left[\frac{pcs}{hr}\right] : i \rightarrow j\ and\ \ j \rightarrow i$

$c_{ij} = cost\ of\ tranportation\ per\ unit\ of\ flow\ and\ distance\ \ \left[\frac{\$}{pcs * m}\right]$

$$p_{ij} = c_{ij} * Q_{ij}$$

$$Z = \sum_{i} \sum_{j} c_{ij} * Q_{ij} * D_{ij}$$

$D_{ij} =$ rectilinear $distance\ between\ departments\ i \rightarrow j\ in\ meters\ [m]$

In our case of study the flow matrix has been already rescaled based on the bulkiness of the piece that needs to be transported, for this reason and for sake of simplicity the cost of transportation will be set equal to 1 and the resulting cost function will have only a symbolic value that will be used for the benchmarking of the alternative solutions. Through the excel add-in previously described an automatic computation of the cost of the base layout is shown in Figure 46. As it can be seen the cost is Z = 50269 [$/hr].

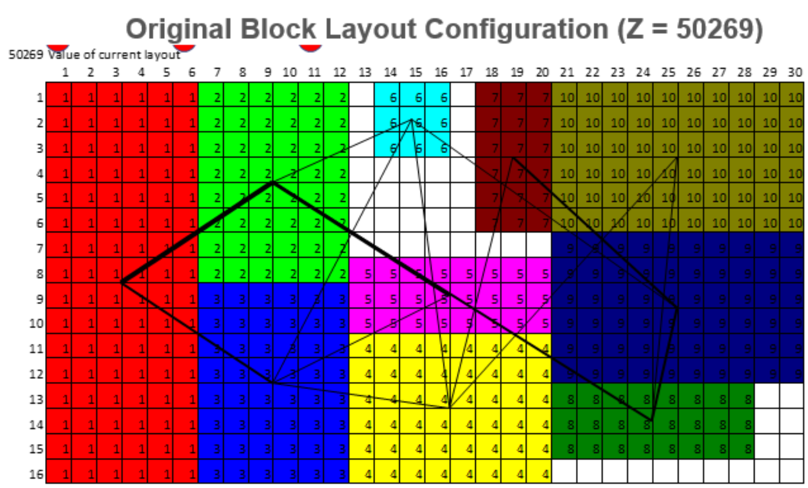


Figure 46, Original Block Layout's cost (SLP)

Once the original layout as been assessed it is time to generate some alternatives based on the space-relationship diagram previously constructed:

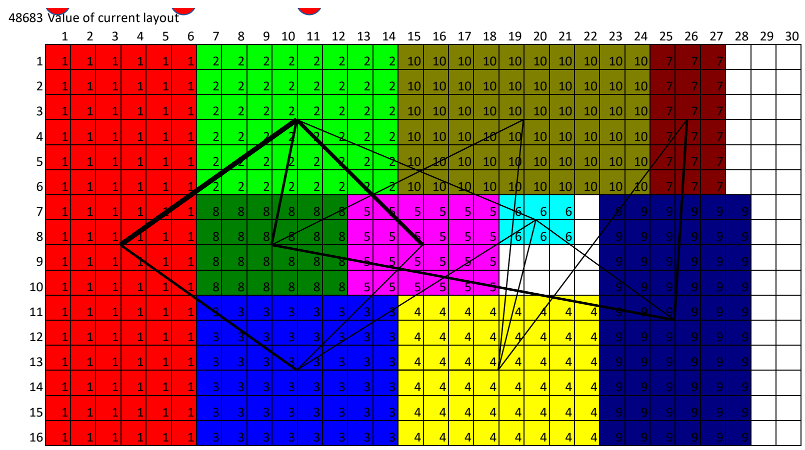


Figure 47, Layout Alternative A (Z=48683)

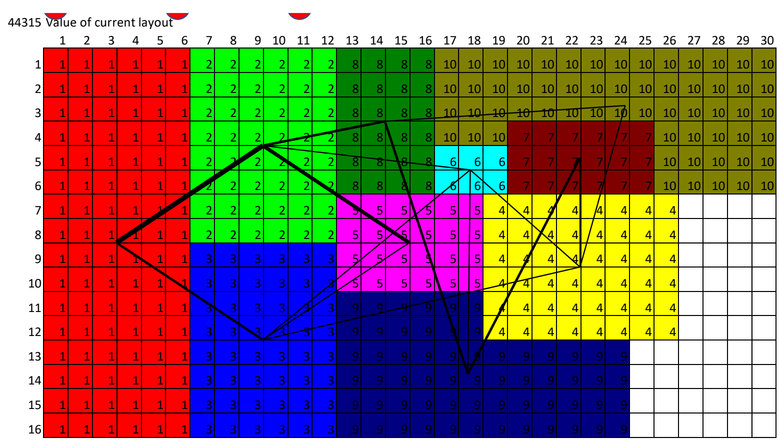


Figure 48, Layout Alternative B (Z=44315)

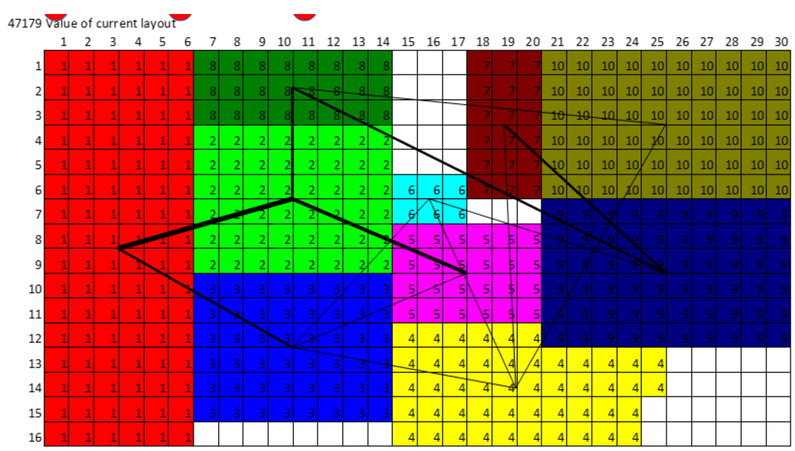


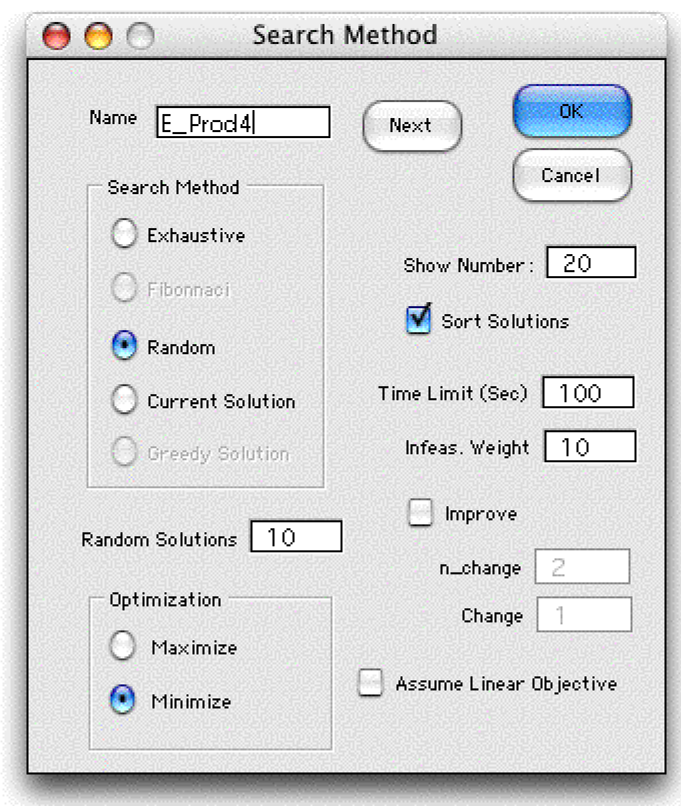
Figure 49, Layout Alternative C (Z=47179)

It is easy to see how each one of the three proposed layout alternatives will reduce the value of the cost function, obtaining a positive impact on the material flows inside the department and reducing the average walking time of the operators. In the decision-making method that this thesis is proposing, the choice and adaptation of the final layout alternative will be addressed after completing the next branch of the static facility layout planning procedure, meaning that the Muther's SLP procedure will stop here and step 8 and 9 will be addressed later on.

Combinatorial Search Procedure

This third and last branch of the proposed static facility layout planning procedure is addressed for a more extensive search for the optimum of a sequential layout. It is necessary to specify that the layout solution obtained starts from a sequential composition of the original layout since the aim of these third procedure is getting a well optimized solution that minimizes the cost function as much as possible. Even though, this approach brings as a drawback that the solution will be very detached from the real life and practical application. Still it will be useful to comprehend the whole picture. To use the methods described on this page the *Optimize* and *Layout* add-in must be used in excel (**The Method**, page 48).

Table 9, search method



The *Optimize* add-in generates 10 random permutations and the *Layout* add-in evaluates them. The best of the 10 are placed on the combinatorial form. The 10 solutions appear to the right of this display (Table 10, First 10 solutions).

Table 10, First 10 solutions

Best Obj.: 4212 Best Found
Search time: 1 seconds
Runs: 11 um.: 11 Imp.: 0
Complete: 100%
Stop Interval: 100

Sorted Feasible Solutions

Run	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	Obj.
10	5	6	4	10	3	8	9	7	2	1	4212
11	5	6	4	10	3	8	9	7	2	1	4212
4	1	6	8	2	7	10	4	9	3	5	4307
3	1	2	5	3	6	8	7	9	10	4	4482
8	9	8	10	3	2	7	5	1	4	6	4519
2	5	9	4	10	2	7	8	3	1	6	4550
7	2	5	4	9	3	8	7	10	6	1	4557
5	1	6	3	4	9	10	7	8	5	2	4701
9	8	7	4	6	1	3	5	9	2	10	4918
6	4	1	7	8	5	3	10	6	9	2	4951
1	2	8	10	7	3	5	6	1	4	9	5120

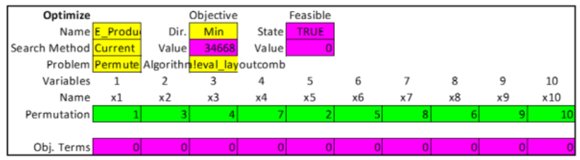
As already introduced at page 48, the program continue in his search for the optimum by starting from the best random result and choosing the improvement option that tries all 2 and 3-change variations of the layout. The process first tries all 2-change variations and whenever a change results an improvement, the two permutation positions are switched in value. The process continues until no 2-change switch results in improvement, then all 3-change switches are evaluated. The program terminates when a complete run through the changes results in no improvement.

Table 11, Combinatorial search (2-switch)

Best Obj.: 34668 Current Sol. with Improvements
Search time: 36.32 seconds
Runs: 186 :num.: 2 Imp.: 184
Complete: 100%
Stop Interval: 100

Sorted Feasible Solutions

Run	Obj.	x1	x2	x3	x4	x5	x6	x7	x8	x9	x10
123	34668	1	3	4	7	2	5	8	6	9	10
186	34668	1	3	4	7	2	5	8	6	9	10
114	34744	1	3	4	9	2	5	8	6	7	10
89	34924	1	3	5	9	2	4	8	6	7	10
88	37110	1	3	5	9	2	4	7	6	8	10
79	37653	1	3	5	9	2	4	6	7	8	10
53	38088	1	3	5	9	4	2	6	7	8	10
43	38113	2	3	5	9	4	1	6	7	8	10
42	41004	2	3	5	9	4	1	8	7	6	10
32	41219	2	3	5	9	4	1	7	8	6	10
26	42722	2	3	5	10	4	1	7	8	6	9
1	44318	2	3	9	10	4	1	7	8	6	5



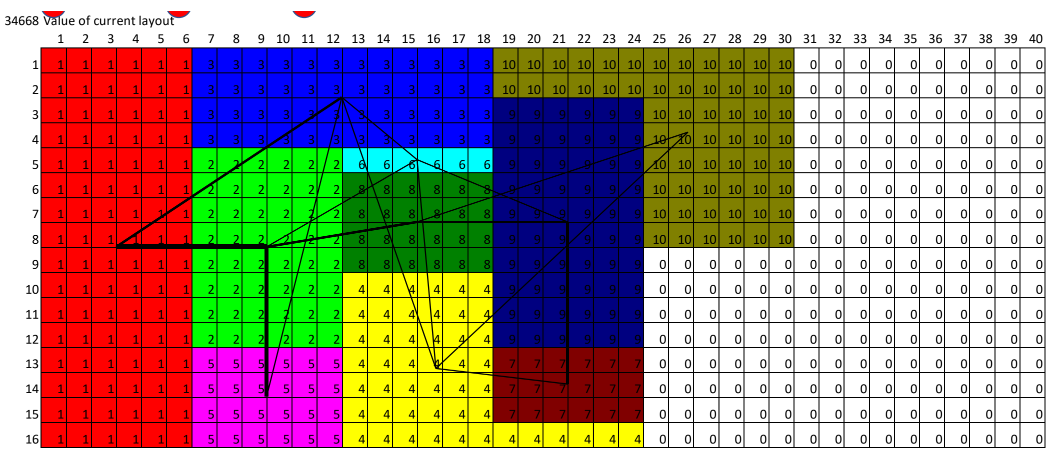


Figure 50, Pairwise exchange layout's improvement (Z=34668)

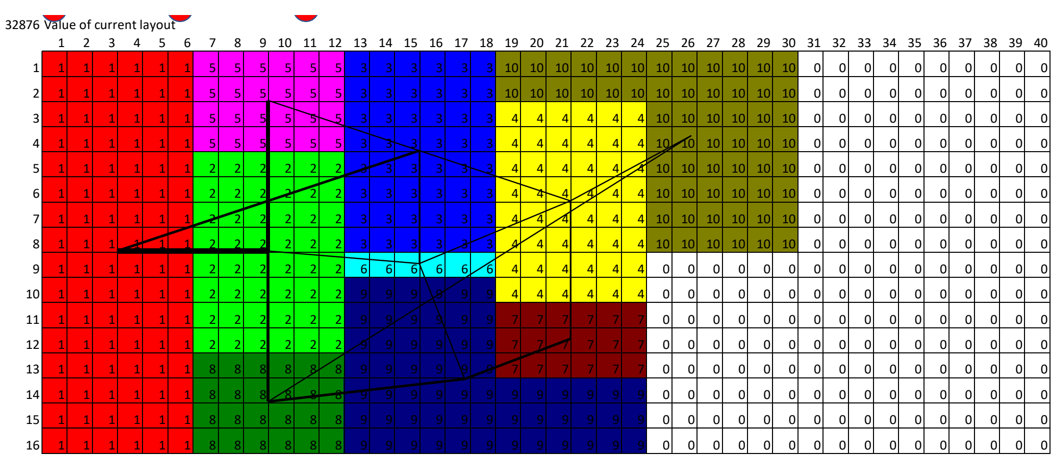


Figure 51, Layout's 3-switch improvement (Z=32876)

Once both the *graph-based layouts* and the *combinatorial search layouts* solution are available, it is interesting to address some key point regarding the possible improvements before moving to the actual proposals:

- The FFC Packaging Station (dep. n.8) is always positioned close by the supply of kiln-carts (dep. n.1) and the inspection (dep. n.2).
- The Pallet dispenser and the packaging material for the VCs (dep. 6) always occupies a central position inside the department’s area.
- The Gluing Station (dep. n.4) occupies different positions in each configuration, mostly far from the input department n.1.
- The WIP storage and the cardboard storage occupies flexible locations in each configuration, it could be an option to split them to reduce operational and cycle times.

By computing a rough estimation we can say that a re-layout investment could decrease the total distance travelled by the operators during the day up to 5-10%, based on the assumption of a stable production flow from the data collected in the last four months with the characteristic that have been considered above. Moreover, in Figure 52 it can be seen how much each solution could potentially contribute to the overall material handling and transportation reduction.

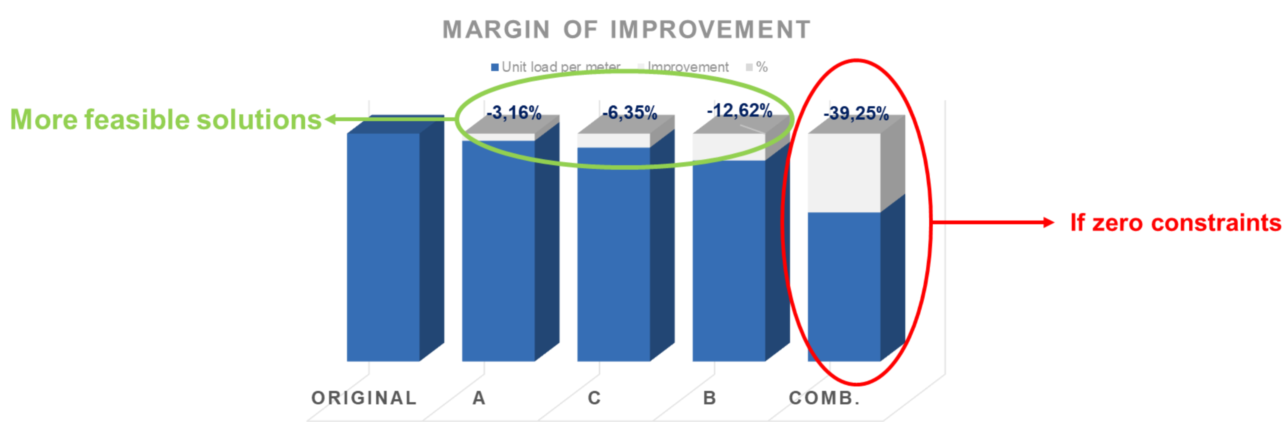


Figure 52, margin of improvement and constraints

Integrated Layout Alternative Solutions

In this sub-chapter a horizontal integration between each parallel branch of the SFLP procedure will be developed and the three final re-layout solution for the FFC inspection and packaging department will be described. These three solutions will differ in terms of cost and time of implementation, but they will be applicable and result-oriented when it comes to optimizing the production flow and re-organizing operations and ergonomics.

Lean Material Handling Re-Layout (A)

The first alternative to be presented is the *Lean Material Handling Re-layout* solution. This solution entails the objective of increasing the speed and ergonomics of material handling and transportation by following the layout advices taken from the *SLP* and the *combinatorial search* procedure. It also follows the suggestion of the *lean approach* concerning the removing of the unused gluing station to improve the area efficiency. More in detail, in this solution, the FFC packaging operations are performed with the help of a new lifting tool directly after having inspected the piece, allowing for a reduction of the overall number of lifts. Moreover, the gluing station is removed from the main area and positioned where cardboards are currently stored. Finally, some new shelves are added close to the packaging station to reduce waste in cardboard transportation.

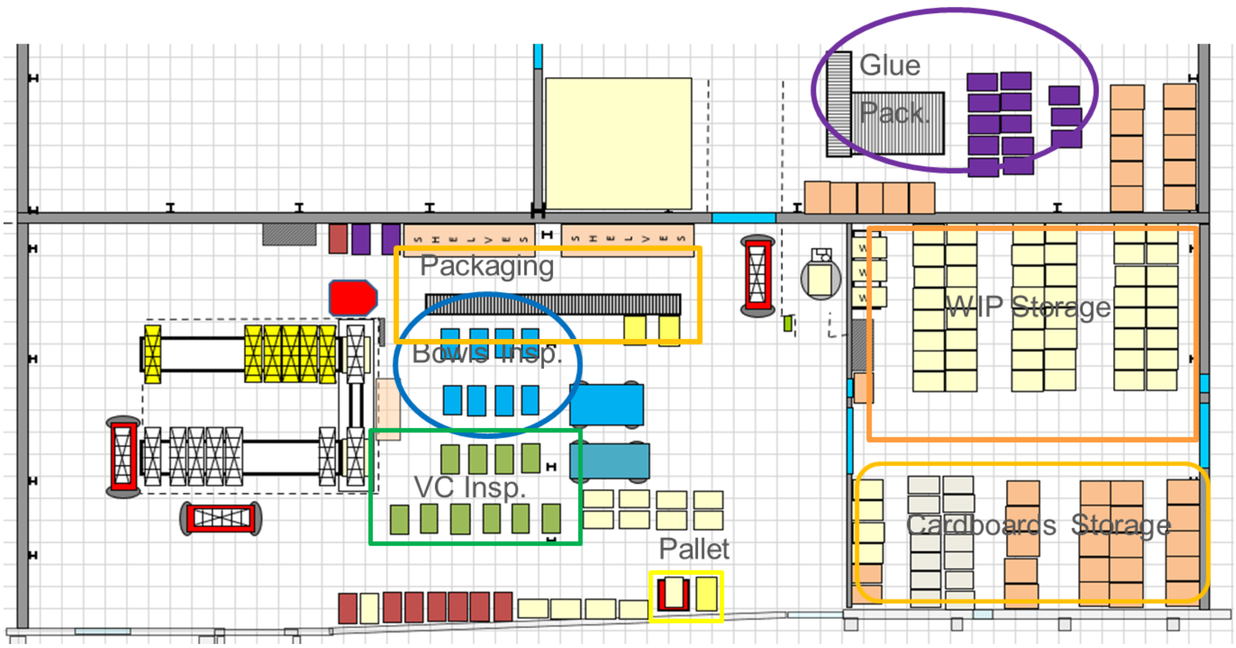


Figure 53, Alternative A

Advantages:

- Reduced material handling by performing FFC packaging immediately after inspection.
- Better ergonomics.
- One touch flow between inspection and packaging.
- The pallet storage is kept in the middle of the department to decrease the total distances.
- Small step installed in the inspection workplace to improve speed and ergonomics.

Disadvantages:

- Less intuitive layout division.
- Need to check how much space is needed for the shelves.
- Need to improve communication to forecast FFC models.

Cost Estimation (33’750 eur):

- Installation and purchasing of the New Tool – 30’000 eur
- Moving Packaging Station – 750 eur
- Moving Gluing Station – 2’500 eur
- Adding Shelves – 500 eur

Compact Packaging Re-Layout (B)

This second alternative solution aims at simplifying the complexity in the department by separating inspection and packaging operation in two distinct areas. As a matter of facts, in this solution the gluing station is removed from the main area and positioned where packaging operations are currently performed, as suggested by the *lean approach* results. Moreover, a new lifting tool is installed in the packaging/gluing area facilitating the lifting operations and allowing only one operator to perform the packaging operation, since in the current situation the packaging is performed manually (too heavy for one operator). Finally, some new shelves are added close to the packaging station to reduce waste in cardboard transportation.

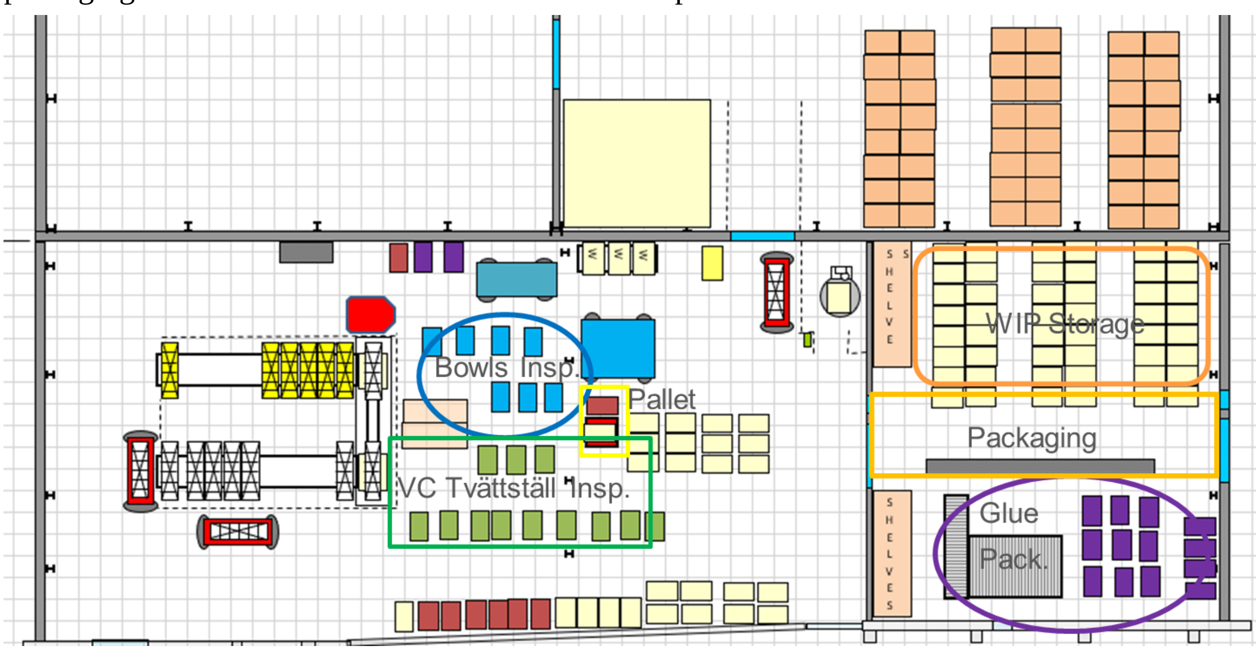


Figure 54, Alternative B

Advantages:

- 3 clearly separated areas
- The layout is more intuitive and easier to understand

- Some shelves are added into the packaging area to decrease the movement of the operators
- Areas divided based on volumes out of the kilns (Product Family A, B, C)
- The pallet storage is kept in the middle of the department to decrease the total distances
- More space available (even for a third storage line for packaged VC)

Disadvantages:

- The material handling of the FFC is not optimized, since parts must be moved twice (once to be inspected and once to be packaged)
- Need to check how much space is needed for the shelves
- Cost of installation of Material handling tool in the packaging area

Cost Estimation (40’500 eur):

- Installation and purchasing of the New Tool – 30’000 eur
- Installation of ceiling rails – 7’500 eur
- Moving Gluing Station – 2’500 eur
- Adding Shelves – 500 eur

Separated Flows Re-Layout (C)

This third and last alternative solution is based on the observation that production volumes are distributed as a pareto curve, meaning that few products called “high runners” occupies 80% of the volumes (bowls), while most of the product variety occupies only a 20% of the inspected pieces in the department. In this solution the flows between bowls and washbasins are split after inspection and the FFC packaging operations are performed with the help of a new lifting tool directly after having inspected the piece, allowing for a reduction of the overall number of lifts. Moreover, all the material handling, transportation and pallet formation of the bowls is automated and the gluing station is removed from the main area and positioned where cardboards are currently stored. Finally, some new shelves are added close to the packaging station to reduce waste in cardboard transportation.

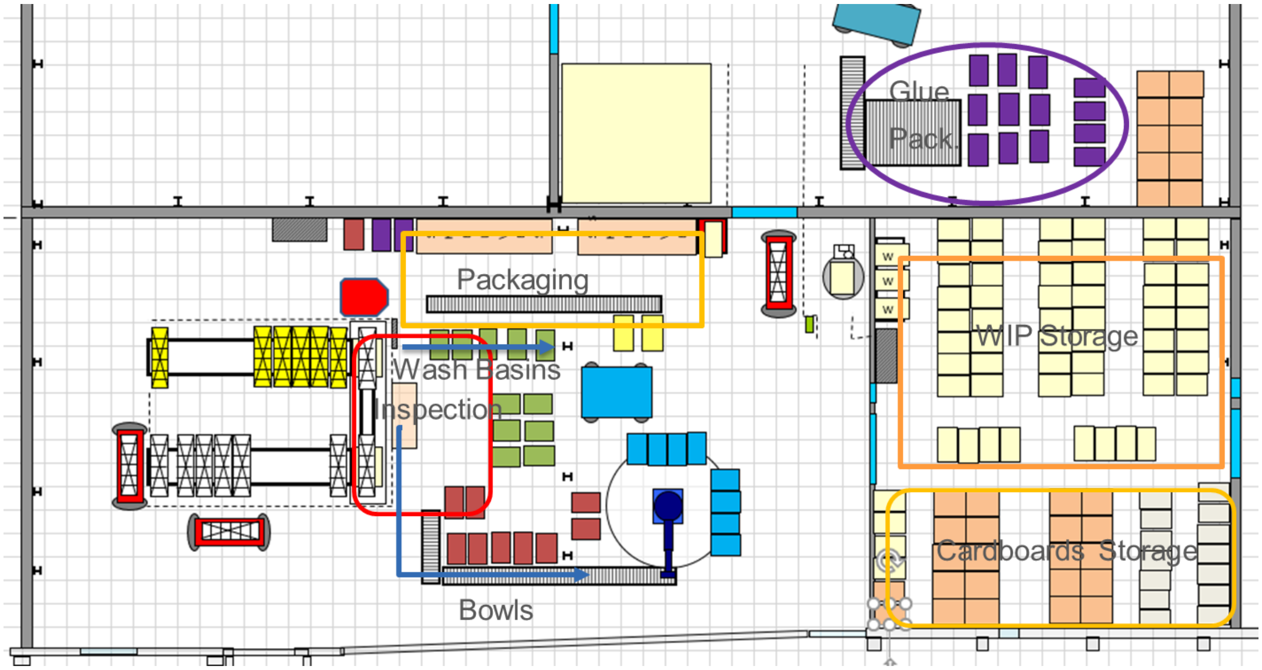


Figure 55, Alternative C

Advantages:

- Improved version of Lean MH re-layout.
- Higher inspection capacity of the department.
- Divided volumes allow a smoother flow in the inspection department.
- More intuitive flows, WB vs Bowls.
- Need only 1 operator to run at standard rate.

Disadvantages:

- Cost of installation is way higher than the other two options.
- Need to check how much space is needed for the shelves/robot station.
- It makes sense only if bowl's volume/variety ratio keeps very high, meaning few models but with very high volumes out of kiln 21.

Cost Estimation (243'750 eur):

- Installation and purchasing of the New Tool – 30'000 eur
- Moving Packaging Station – 750 eur
- Moving Gluing Station – 2'500 eur
- Adding Shelves – 500 eur
- Automated Conveyor System – 10'000 eur
- Installation and purchasing of Robot for Material Handling – 200'000 eur

Qualitative Feedback Collection

Once the three layout alternatives have been generated by integrating the suggestions and solutions from the three different branches of the SFLP approach, a qualitative feedback is collected from the management team of the production site. This feedback is collected through a questionnaire as described in the Appendix N.1; each member of the management team is asked to grade from 1 to 5 some key success factors based on their own experience on each solution. The Key Success Factors are resumed as follows:

- ***Flexibility***: a flexible facility can be defined as a facility that can readily adapt to changes without significantly affecting performance.
- ***Robustness***: a robust facility is one that behaves well over a variety of scenarios and outcomes.
- ***Economic Effort***: intended as a grade of how costly each solution would be in terms of invested resources (money, workforce involved etc.).
- ***Time for Implementation***: intended as a grade of how long each solution would be in terms of project duration.
- ***Ergonomics***: parameter that describes the work conditions of the worker performing inspection and packaging operations on daily bases (meters walked, number of lifts etc.)
- ***Performance Improvement***: parameter describing the efficiency of the solution in terms of potential throughput and kilns speed regulation (pcs/day, kiln-cart/hour etc.)

A final grading of the three solution is performed through a *Factor Rating Method,* where based on the weight given to each criteria, a weighted average is performed and a final value is compared for each solution. In the list below the roles of the participant to the feedback session:

- Managing Director
- Production Manager
- Technical Manager
- Project Manager
- GPS Engineer

Factor-Rating method

This methodology for multicriteria evaluation comes from the location factor rating system, where factors that are important in the location decision are identified. Each factor is weighted from 0 to 1.00 to prioritize the factor and reflect its importance. An objective score is assigned (usually between 1 and 5) to each factor based on its result in comparison with the other layout alternatives, and the weighted scores are summed up.

Six steps in the method:

1. Develop a list of relevant factors called key success factors
2. Assign a weight to each factor
3. Develop a scale for each factor
4. Score each location for each factor
5. Multiply score by weights for each factor for each location
6. Recommend the layout with the highest point score

The results of this qualitative feedback analysis produced solution A as best in the ranking followed by solution C and B with quite similar score. This result can be resumed from the fact that almost all the team agreed on the cheapness and fast implementation of solution A with respect to the other two. Another interesting point is related to the fact that the value of productivity in solution C is perceived equivalent or slightly better than solution A one. Moreover, ergonomics resulted to be a penalizing factor for solution B, mostly due to the necessity of lifting twice the washbasin during operations.

Table 12, Factor Rating Method output

	Robustness	Flexibity	Economic Effort	Time for Implementation	Ergonomics	Productivity	TOT Score
A	4	4	5	5	4	4	4,35
B	3	4	4	4	3	3	3,5
C	4	3	2	2	5	5	3,5

Dynamic Facility Layout Planning

After having collected a qualitative feedback from the management the next step in the decision-making method is to implement a quantitative analysis of the three alternative solutions proposed in the chapter *Integrated Layout Alternative Solutions*. The analysis will take advantage of a simulation software called AutoMod (see Appendix 2 for more detailed information regarding the software) and thanks to this software three different improvement models will be programmed and tested in different scenarios and finally compared with each other to benchmark three main key indicators:

- ***Robustness***: this parameter will be assessed by looking at the contraction and expansion of some key indicators during the testing of the solutions under different product mix scenario (% of increment average number of pieces in the buffer).
- ***Timeliness***: this parameter will be assessed by looking at the average time a piece has to wait to be processed by an operator.
- ***Work in Progress***: this parameter will be assessed by looking at the average number of pieces that wait in the conveyor buffer before being inspected.

The DFLP benchmarking will take place in first place throughout a comparison between the current asset's and the three improved models' performances at three different level of speed (based on the kiln's output).

1. Low Speed (23 hours) = 11 [min/kiln-cart]
2. Medium/Regime Speed (20 hours) = 10 [min/kiln-cart]
3. High Speed (18 hours) = 9 [min/kiln-cart]

These speed levels are based on the performance of kiln 21 inside the Bromölla's plant, in particular the speed of that kiln cannot go below 18h since fire fine clay models are being processed there and below such a speed there would be a too high number of cracks and defects. After having compared the performance with the As-Is situation, three possible future scenarios are designed. In each of these three scenarios the Pmix is modified keeping the same regime speed. Finally, several runs for each model are performed with a predetermined snap length in order to have statistically reliable data (up to 95% confidence interval). In each scenario there will be a best and worst solution and, by performing a weighted average of each score, one final solution will be suggested. All the results gained from the simulation have been collected on a 150 days length of the simulation combined with a number of six simulation runs for each measure. This procedure was followed each time a change in the simulation parameter was addressed, in order to have statistical reliability of the obtained data, due to the fact that stochastic variables where introduced in the scripts. The next chapter will present the results of the simulation runs firstly in the current composition of the layout and in second place in all the three-improvement version proposed after the SFLP.

Current Layout Performances and Scenario Planning

In this sub-chapter the current layout is tested at the three speed levels (Table 13) and the boundary conditions are introduced. Moreover, the three planned future scenarios are described and justified.

Table 13, Speed Levels

	Speed [min/kilncart]
Low	11
Medium	10
High	9

As we can from the results of the simulation (Table 14 and Table 15) the current model is able to perform only at the first two speed levels and finds the high-speed level too stressful to be computed in a reasonable amount of time. For this reason, we can tell that the current scenario cannot withstand the speeds below or equal to 9 min/kilncart and an improvement solution should fulfil at least this duty in order to achieve high throughput.

Table 14, Low Speed Performance - Current

STATISTICS (LOW SPEED)	Q_buffer Average	Q_buffer MAX	Q_buffer Av_Time
Average	8,92	56,67	912,64
Standard Deviation	0,17	4,32	15,08
Sample Size	6,00	6,00	6,00
Confidence coeff.	1,96	1,96	1,96
Margin of err.	0,13	3,46	12,07
Upper bound	9,05	60,12	924,71
Lower Bound	8,78	53,21	900,57
Max	9,10	63,00	931,00
Min	8,66	51,00	889,43
Range	0,44	12,00	41,57

Table 15, Medium Speed Performance - Current

STATISTICS (MEDIUM SPEED)	Q_buffer Average [pcs]	Q_buffer MAX [pcs]	Q_buffer Av_Time [sec]
Average	20,36	120,50	1893,55
Standard Deviation	1,62	12,28	151,32
Sample Size	6,00	6,00	6,00
Confidence coeff.	1,96	1,96	1,96
Margin of err.	1,30	9,82	121,08
Upper bound	21,66	130,32	2014,63
Lower Bound	19,06	110,68	1772,46
Max	22,05	138,00	2049,00
Min	18,23	109,00	1693,00

Range	3,82	29,00	356,00

Apart from testing the As-Is situation the decision-making method developed entails the benchmarking between the solutions also based on different forecast of changes in the product mix. This will give to the final solution an assessment to dynamic changes and uncertainties that will help in the choice's justification. Each scenario that has been forecasted is divided into three years' steps, where in each step the change is duplicated to intensify the stress on the layout's performance.

The first scenario is shown in Table 16 and it represents the eventuality of removing VC washbasins , wall hanging bowls and FFC to be glued from the department's inspection and packaging operations. The 1st year a 75% of floor standing bowls and a 25% of FFC models is fired in kiln 21 while in the next years we se firstly a reduction of 5% in the volumes of the FFC and an increase of 5% in the bowls, same for the last year where the Pmix stabilize with a 10% expansion and reduction respectively with respect to the 1st year percentage.

Table 16, Scenario n.1

Scenario n.1	%FS Bowls	% FFC Pack	%VC washbasins and WH bowls	%FFC glue
1st year	75%	25%	0%	0%
2nd year	80%	20%	0%	0%
3rd year	85%	15%	0%	0%

The second scenario aims at testing a totally different Pmix composition, in particular in this case the FS bowls decrease their volume in exchange of a balanced increase of all the other products (Table 17). The starting composition in this case is similar to the original one but with a more balanced percentage, the aim is testing the solution while increasing the Pmix variety and complexity.

Table 17, Scenario n.2

Scenario n.2	% FS Bowls	% FFC Pack	%VC washbasins and WH bowls	%FFC glue
1st year	57,5%	18,0%	18,0%	6,5%
2nd year	55,0%	19,0%	19,0%	7,0%
3rd year	50,0%	21,0%	21,0%	8,0%

Finally, in the third and last scenario an expansion of the FFC (both pack and glue) volumes is forecasted with a parallel decrement of the bowls and vitro china models more in general (Table

18). Thanks to this last scenario the picture of possible changes in the Pmix is quite broad and accounts for various and different possibilities.

Table 18, Scenario n.3

Scenario n.3	% FS Bowls	% FFC Pack	%VC washbasins and WH bowls	%FFC glue
1st year	57,5%	19,5%	14,5%	8,5%
2nd year	55,0%	22,0%	12,0%	11,0%
3rd year	50,0%	27,0%	7,0%	16,0%

As-Is - Testing of Performance

It is now time to check each improved solution under different speed level and see what the outcome will be. Each one of the three solutions will be tested with the current product mix configuration, but with different speeds of the kiln. This will allow to understand how each model performs with respect to the original.

Model A

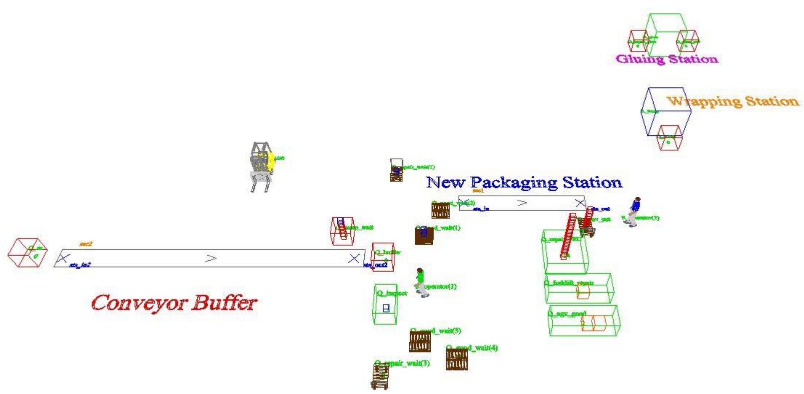


Figure 56, AutoMod Simulation Model A

In this model a new packaging station has been added close by the inspection and it has been forecasted a reduction in the packaging operation of almost 30 seconds per piece, moreover no extra time has to be waited to move the full kart in the packaging station. Also, the picking operations are reduced thanks to the development of a new universal tool for lifting bowls and washbasins. As a drawback the gluing operations are delayed a little since an extra time for moving the kart up to the station is introduced.

Model B

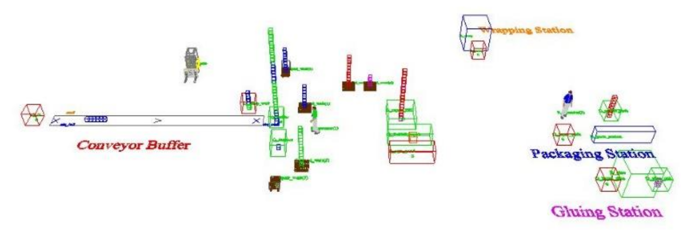


Figure 57, AutoMod Simulation Model B

This model represents the second improved version of the original layout also defined as *compact packaging layout.* In this solution the gluing station is removed from being close by the inspection and is placed in the current packaging area. Moreover, a lifting tool must be installed in that area to facilitate operations an ergonomics.

Model C

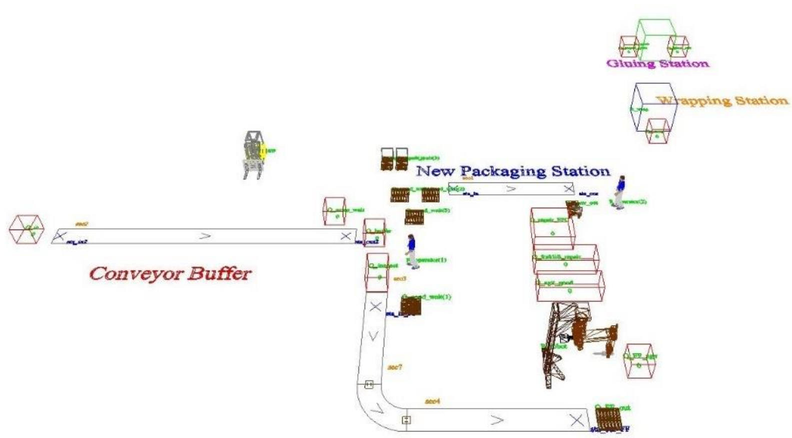


Figure 58, AutoMod Simulation Model C

In this third model an automated conveyor system with a robotic arm is simulated for the bows material handling and palletization. The advantage of this situation concerns a reduced amount of time for the bowl’s post-inspection phase. In this configuration the flows are divided into wash basins and bowls in order to decree complexity.

These are the results keeping the as-is status of the Pmix:

Table 19, sum of load's average waiting time for operators

R_1&2 Av_Wait [sec]	Low	Medium	High
C	143,840	147,012	148,732
B	274,562	283,218	291,280
A	141,242	144,870	147,843

Table 20, Average pieces in the conveyor buffer

Q_buffer Average [pcs]	Low	Medium	High
C	4,507	6,038	10,705
B	5,413	8,668	37,552
A	4,628	6,283	11,213

Table 21, Percentage of standard deviation between the 3 levels of speed

% of STDEVA	**Q_buffer Average**	**Q_buffer MAX**	**Q_buffer Av_Time**
C	45,580%	39,815%	35,453%
B	102,785%	80,676%	95,089%
A	46,448%	30,959%	37,060%

By looking at the results of the simulation we can already tell that all the layout configuration proposed brings a general improvement in the overall performance of the department. First of all, each of these simulation models were able to run even at high speed of the kiln. In particular the two configurations A and C, with the packaging close by the inspection, yield better and quite similar performance that remains quite stable even at high speeds, meanwhile layout B yielded worse performance especially at high speed setting.

Scenario N.1 - Testing of Performance

After having tested the layout's performance in the current Pmix configuration it is time to challenge each layout under different possible future changes. In this chapter and the next one, only the results of the simulation will be shown and commented. Before starting with the results, it is better to clarify what we are going to analyse. As already introduced, the dynamic testing of the three layout solution has been developed throughout the comparison of three parameters: percentage of expansion/contraction of the Q_buffer performances (graph on right of Figure 59), quantity of average work in progress in Q_buffer (top left graph in Figure 59) and finally the average time a load must wait for being processed by an operator (bottom left graph in Figure 59).

The choice of these three parameters should be representative respectively of: *robustness*, *work in progress* and *timeliness* of each layout alternative solution.

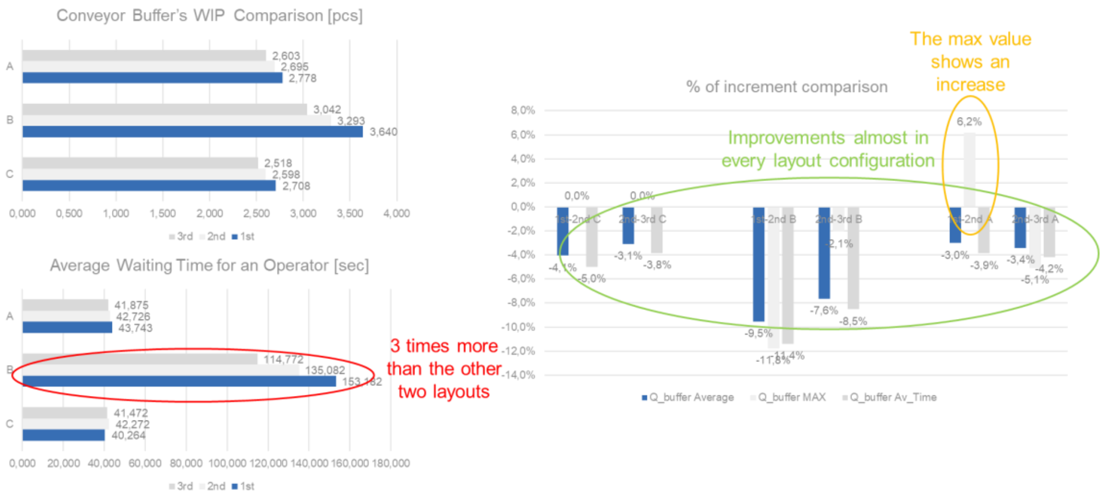


Figure 59, Results under Scenario N.1

It can be seen from Figure 59 that three main parameter have been tested and compared: the Conveyor Buffer average work in progress, the average time a piece waits for being processed by an operator and finally the percentage of increment/decrement between years with respect to Conveyor Buffer performances. By looking at the picture it can be said that by testing a scenario in which the Pmix is reduced at two product families only (floor standing bowls and FFC packaging models), the result is an overall improvement in each of the tested models. Moreover, it can be said that model A and C yield way better results with respect to model B, this is evident when we look at the average waiting time that in model B yields three times more seconds then in the other two models. To sum up, it can be addressed that in this first scenario all the models perform better than in the current Pmix configuration and even though model B improves the most, still it yields lower performance with respect to model A and C.

Scenario N.2 - Testing of Performance

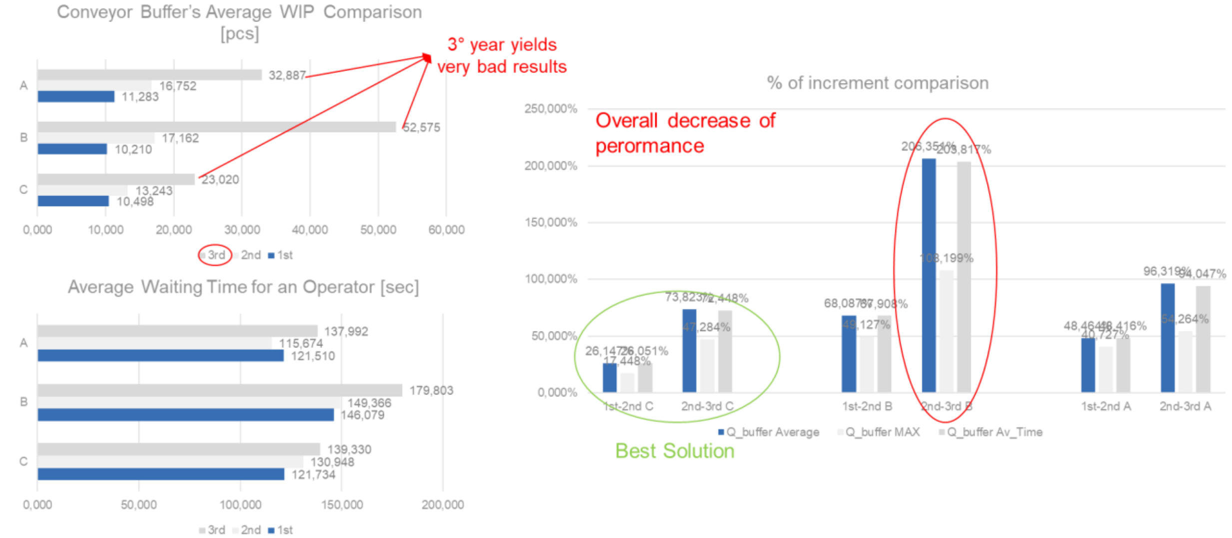


Figure 60, Results under Scenario N.2

In this scenario testing, it can be seen how the overall trend is a decrease in the buffer's performance in each one of the models. If we look at the buffer average WIP, it is interesting to see that the Pmix change in the third year causes a steep increase in the number of pieces waiting in the buffer before the inspection phase, this shows how this scenario increases the complexity of operations with the department. As a result we can tell that layout C yields the best performance closely followed by layout A, while the third and worst configuration is again the layout B where an increase of more than 200% in the average number of pieces waiting for inspection is registered.

Scenario N.3 - Testing of Performance

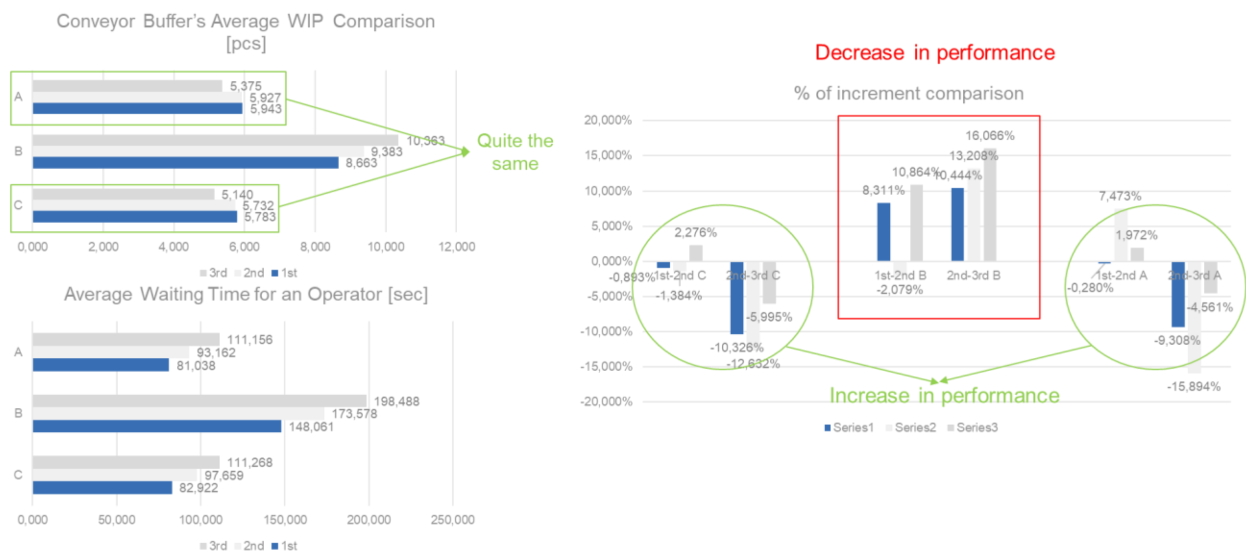


Figure 61, Results under Scenario N.3

For what concerns this last scenario it can be seen from Figure 61 that opposite trends arise in each layout alternative solution. Both layout A and C shows an improvement trend year by year, meanwhile layout alternative B shows up to 10% increase in buffers work in progress and average waiting time. Even in this last scenario the output of layout B achieves the worst performance in every year showing instability to change in every form of product mix. It is interesting to confirm that layout A and C achieves instead rally good outputs, and rather close to each other as already seen in the previous tests.

Before comparing all the results together and deciding which layout could best fit the future investment, it is good to resume the dynamic facility layout planning outcomes. It is important to address how each year of each scenario has been simulated for 150 days for 6 times in order to account for uncertainties related to a stochastic process, as a matter of fact each solution is reliable within a 95% confidence interval. We can tell that even though each scenario has been tested with different arrangements of Pmix, the behaviour of the solutions is quite similar, as a matter of facts solution A and solution C always achieve good results in each of the tested conditions while layout solution B does not keep pace. It is interesting to notice how the performances of solution C are only slightly better the those of solution A even though the cost and time for its implementation are way higher.

Factor Rating Method and Final Layout Choice

In this last sub-chapter, the overall results of the qualitative and quantitative analysis are resumed and a final choice is made again based on a factor rating process that takes into account multiple aspects and sums up one best solution, based on the practical constraints and theorical outcomes. As it can be seen from Table 22, Key success factors, six main parameters are accounted for and each one of them has a certain weigh that represents its relevance in the final choice.

Table 22, Key success factors

Cost of the Solution	0,3
Qualitative Feedback	0,2
As-Is Testing	0,2
Scenario n.1	0,1
Scenario n.2	0,1
Scenario n.3	0,1

Once the weights are set, each one of the layout solutions is ranked from 1st to 3rd in each of the different criteria and an overall score is assigned to clarify which solution will achieve the best result. In this case the weights of each criteria have been assigned based on the company needs, but they can be readjusted in different ways. In this project the final rank is shown below in Table

23, where the first position is achieved by the *FFC Re-layout alternative A*, this mainly due to the fact that this solution achieves the 1st position both in the cost of implementation ranking and it is also the one that achieves the highest score with respect to the qualitative feedback from the management team. Moreover, it strikes almost equal performance as the re-layout solution C when it comes to speeds equal or higher than 18 hours firing time. All these conditions bring the *FFC Re-layout alternative C* at the second position in the ranking, mainly due to its extremely high cost and due to the not so high-performance improvement at this boundary conditions. Finally, the *FFC Re-layout alternative B*, even though it represents an improved version with respect to the original layout, it is with no doubt the worst of the three alternatives in all aspects and for this reason it achieves the third and last position in the ranking.

Table 23, Final Ranking

Layout Options	Rank
A	1st
C	2nd
B	3rd

The Result - A Two Step Proposal

Once a multifactor benchmarking has been addressed and a final solution is chosen, it is interesting to see how we expect this solution to work. The main goal of the winning *FFC Re-layout alternative A*, also named *Lean Packaging Layout*, concerns the reduction of the number lifting during the inspection and packaging operation. Moreover, this solution allows a reduction of the overall work in progress thanks to a reorganized allocation of space in the main area. The removal of the gluing station frees a lot of space that is reused in a more efficient way and, thanks to the use of shelves close by the packaging station, only the necessary material can be stored allowing for a more compact working area. Improving communication between departments is almost mandatory in this solution since *just in time* packaging is the final aim. For this reason, a fast and frequent exchange of information with glazing department must be implemented and projected on the main monitor of the department. Finally, the installation of a new tool (see Figure 62) will speed up packing and dropping operations, no set-up between different washbasin models will be needed.

In the final meeting with the management team of the plant, a two-step solution has been proposed. In particular, the cheapest and best fitting *FFC Re-layout alternative A* has been proposed as first step for improving the department's layout. This solution is expected to cost around 35'000 euro and its implementation should last no more than 3 to 4 months overall. Consequently, the *FFC Re-layout alternative C* can be a second step solution where the path performed by the bowls after inspection is completely automated in terms of transportation and material handling inside and outside the department. More specifically, this second step would require a much higher time and cost for its implementation (6 to 10 months and up to 250'000 euro) and such an investment could be justified only if the kiln could run at higher speed such as 14 hours firing time (same as kiln 19 and 20). If the firing time is set equal or higher than 18 hours, the performance improvement does not justify the investment. After discussing the results with the management team of the plant, they decided to implement the first step starting from August 2020 and they appreciated the 2nd step proposal, but no implementation was planned in the short term.

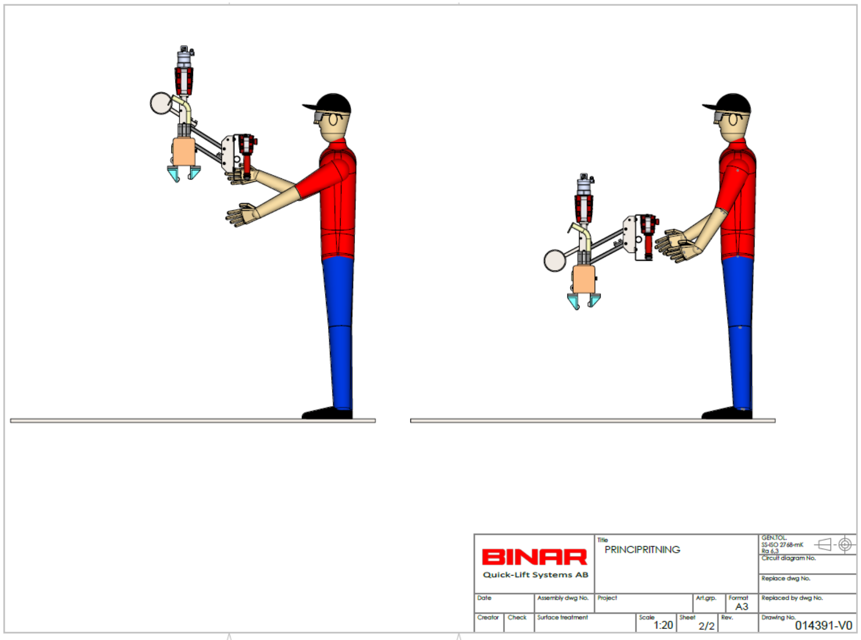


Figure 62, Lifting Tool FFC Department

Conclusion

In this last chapter the process and structure of the thesis is recalled and the outcomes are presented. The starting assumptions of this project concerned the development of a structured methodology for helping managers or factory planners when addressing problems regarding re-layout optimization and continuous improvement intervention inside a facility or production plant. The idea was to develop a decision-making method that accounted for already existing methodologies in order to generate layout alternatives that would not only optimize the production flow, but would also be robust to future uncertainties. First a brief introduction of the industrial context has been addressed and the ceramic process production described, consequently a wide analysis of the state-of-the-art literature concerning both lean manufacturing and the facility layout problem has been performed. Several tools concerning waste reduction and identification have been described and existing methodologies regarding the layout design and optimization have been highlighted. Main distinctions between static and dynamic facility layout planning were commented and analysed. Once the theoretical bases where set, the decision-making method was constructed in a three-step procedure. The 1st step of this decision making method concerned a *static facility layout planning* procedure with three different branches: lean approach, Muther's SLP approach and Combinatorial search approach; by integrating the outputs of these branches a number of alternative improved re-layout solutions was presented. Out of this first step, three practical solutions were generated: solution A, B and C with different costs and performance has been assessed. The second step concerns a qualitative feedback session where the opinion of the management team of the production site was taken into account through a questionnaire before moving ahead with the dynamic analysis. The opinion was evaluated through a factor rating method based on the questionnaire's outputs. Once the experience-based feedback has been collected, the last step concerning the *dynamic facility layout planning* was addressed. Here each re-layout alternative was quantitatively assessed through the use of a simulation software called AutoMod, firstly with the current Pmix, by changing the speed of the kiln and, after, in three different Pmix scenarios (every scenario has been tested on three years level of intensity of the change). Finally, a factor rating procedure is applied to choose the best re-layout alternative based on multiple criteria, such as the cost of the solution and the various outputs of each simulated scenario. In the last chapter the results of the application case study are presented and the outcome discussed. As a result, the plant management appreciated the final solution of the procedure and decided to implement them straight away: the proposed final choice was divided into a two-step process with re-layout solution A, as first investment, followed by re-layout alternative C, as possible future improvement in case the speed of the kin would be pushed below 18 hours firing time. To sum up, it can be said that this procedure is a standardized decision-making method that could be for sure generalized and applied to other industries and even for block layout of the facility to help managers with process improvement and waste reduction in various facilities.

Appendix 1: Questionnaire on FFC Re-Layout Design Alternatives

The current sheet has the purpose of supporting the quantitative analysis that has been made concerning the upcoming project of continuous improvement and optimization of production patterns in the Fire Fine Clay (FFC) inspection and packaging area. It will be developed in the form of a questionnaire where **3 layout alternatives** will be shown and for each one of them it is asked to **grade some key success factor**. The score should be assigned without a technical analysis of each solution, but only on your qualitative and experience-based opinion.

This questionnaire will be used as a feedback from the factory's management to validate the project's decision-making process.

Thank you for your availability.

What is your role in the factory? ______

For the next several questions, please choose a number from 1-5, and write it close to each statement to indicate how much each layout would score in each different characteristic.

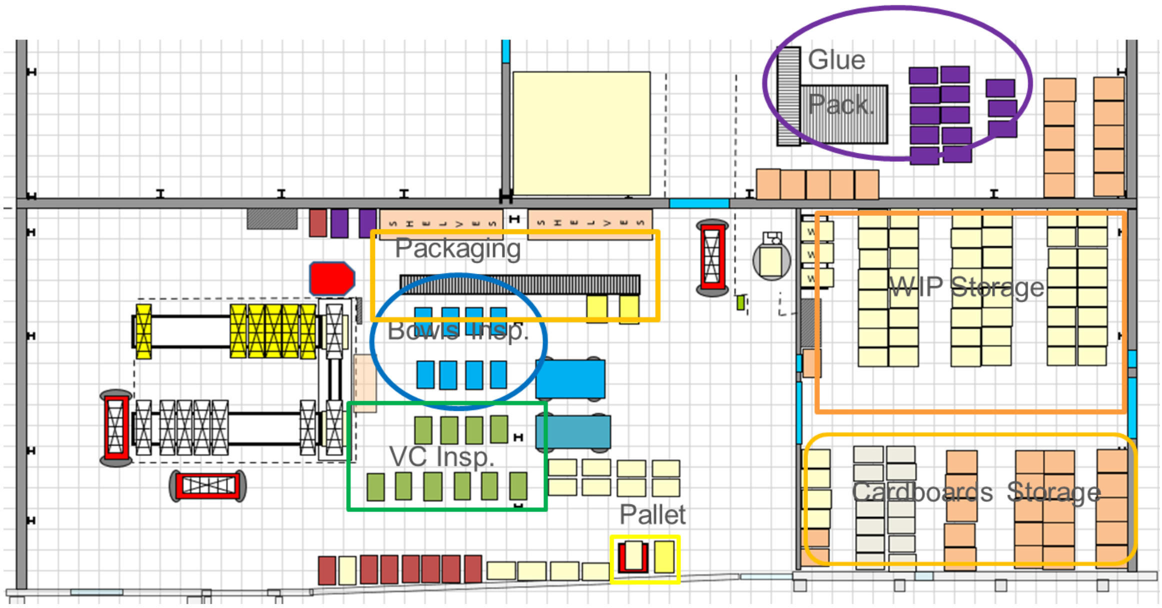
1	2	3	4	5
Low				High

Key Success Factors

Short description of each parameter:

- ***Flexibility***: a flexible facility can be defined as a facility that can readily adapt to changes without significantly affecting performance.
- ***Robustness***: a robust facility is one that behaves well over a variety of scenarios and outcomes.
- ***Economic Effort***: intended as a grade of how costly each solution would be in terms of invested resources (money, workforce involved etc.).
- ***Time for Implementation***: intended as a grade of how long each solution would be in terms of project duration.
- ***Ergonomics***: parameter that describes the work conditions of the worker performing inspection and packaging operations on daily bases (meters walked, number of lifts etc.)
- ***Performance Improvement***: parameter describing the efficiency of the solution in terms of potential throughput and kilns speed regulation (pcs/day, kiln-cart/hour etc.)

FFC Re-Layout Alternative A



In this solution the FFC packaging operations are performed with the help of a new lifting tool directly after having inspected the piece, allowing for a reduction of the overall number of lifts. Moreover, the gluing station is removed from the main area and positioned where cardboards are currently stored. Finally, some new shelves are added close to the packaging station to reduce waste in cardboard transportation.

Grade each parameter with your subjective judgment (from 1 to 5):

____ Flexibility

____ Robustness

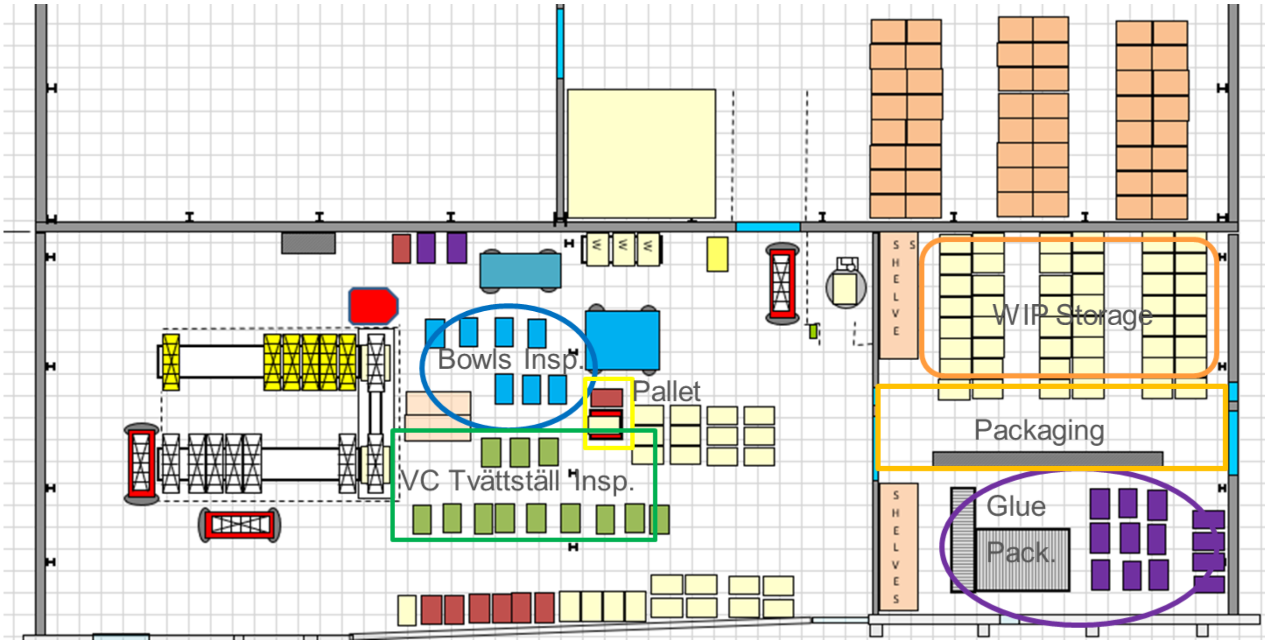
____ Economic Effort

____ Time for Implementation

____ Ergonomics

____ Productivity Improvement (throughput)

FFC Re-Layout Alternative B



In this solution the gluing station is removed from the main area and positioned where packaging operations are currently performed. Moreover, a new lifting tool is installed in the packaging/gluing area facilitating the lifting operations. Finally, some new shelves are added close to the packaging station to reduce waste in cardboard transportation.

Grade each parameter with your subjective judgment (from 1 to 5):

____ Flexibility

____ Robustness

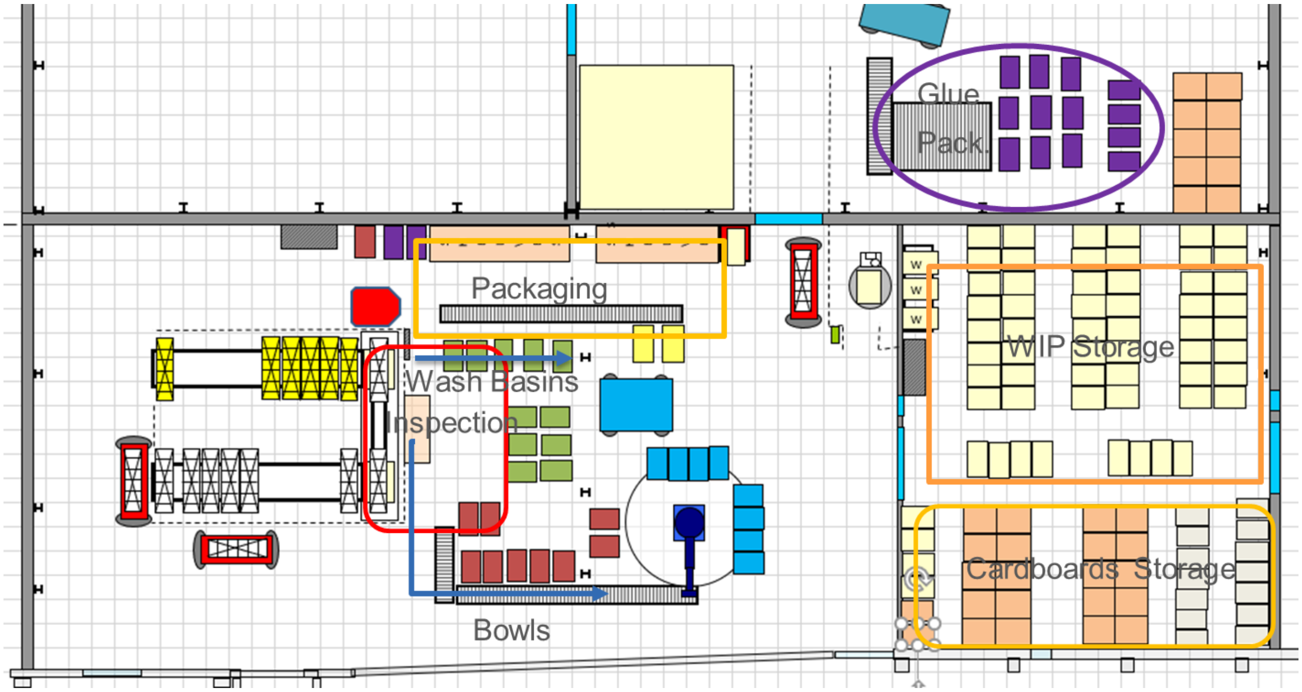
____ Economic Effort

____ Time for Implementation

____ Ergonomics

____ Productivity Improvement (throughput)

FFC Re-Layout Alternative C



In this solution the flows between bowls and washbasins are split after inspection and the FFC packaging operations are performed with the help of a new lifting tool directly after having inspected the piece, allowing for a reduction of the overall number of lifts. Moreover, all the material handling, transportation and pallet formation of the bowls is automated (like flowing factory) and the gluing station is removed from the main area and positioned where cardboards are currently stored. Finally, some new shelves are added close to the packaging station to reduce waste in cardboard transportation.

Grade each parameter with your subjective judgment (from 1 to 5):

____ Flexibility

____ Robustness

____ Economic Effort

____ Time for Implementation

____ Ergonomics

____ Productivity Improvement (throughput)

Appendix 2: Simulation’s Scripts and Modelling

Current Layout Modelling

In this chapter the *current status* of the FFC inspection and packaging department is modelled and the main assumption concerning the simulation are introduced. It is important to clarify that the simulation cannot precisely represent the real complexity that develops inside the department on daily bases, also due to the fact that the process is highly non-standardized and all of the operations are performed manually by the operators. For this reason, stochastic variables are used to represent uncertainties in operational cycle times.

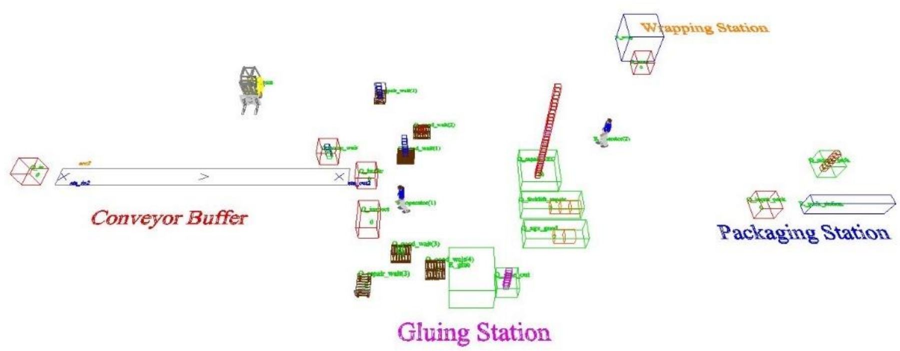


Figure 63, Current Layout - AutoMod Model

Before analysing in detail, the composition of the model’s script and programming, some main assumptions must be introduced:

- In the simulation only 4 product families are taken into account: Floor Standing Bowls, FFC packaging models ,Wall Hanging Bowls and VC washbasin, FFC gluing models and for each of these families the model generates batches with fixed quantity based on a probable volumes estimated out of historical data.
- The simulation model accounts only for what is happening inside the FFC department input and output are not modelled.
- The roles of the two operators are for obvious reasons fixed and well separated, in particular R_operator(1) performs 80% of the inspection full time, while R_operator(2) performs 20% inspection and then does all the material transportation and packaging operations.
- Operator shift and break policy is simplified with a downtime of 20 min every 2 hours and 30 min time

- Moreover, the simulation account only for discrete events to happen as programmed, meaning that uncertainties are hard to model and predict, for this reason normal, triangular, and exponential distribution are introduced inside the model.
- The graphic gives and aid to the user to understand how the system is behaving, but it is not in scale.
- Finally, all the data used for modelling the operations are estimation of real times and are based on the data collected on job floor and experience-based forecasting of possible improvements.

Logic Initialization and Variable Setting

The first step in writing the model's logic is the so-called *model initialization* during this phase two different loads are crated and sent to two separate processes. The first load is L_dummy and is used as a dummy load need to model the operator's breakdowns, the second load L_control is the initiator of the process itself and is sent to the P_init process where the main variables are set with a specific value that will be the same for the rest of the simulation. It is important to highlight the four variable V_bowls, V_VC_wallhang, V_FFC_pack and V_FFC_glue since the represent the percentage distribution that a kiln-cart will have one model or another.

logic

```
//*Model Initialization*//
begin model initialization function
    create 1 load of type L_dummy to P_break /*operators break time*/
    create 1 load of type L_control to P_init /* Start production */
    return true
end

/*Variable Setting*/
begin P_init arriving procedure

 set V_pack = 1
 set V_extra = 2
 set V_extra_glue = 2


 set V_bowls = 60
 set V_VC_wallhang = 17
 set V_FFC_pack = 17
 set V_FFC_glue = 6

 send to P_start
end
```

Figure 64, Logic initialization and variable setting

Kiln Output and Conveyor Buffer

In this second phase the load batches generation out of the kilns is modelled. In particular, this phase of the simulation represents the input source of our FFC department and in Figure 65 you can see that as previously anticipated the load L_control enters a while loop where is cloned into one batch between 4 different load type named: L_bowls (6 pieces) , L_FFC_pack (5 pieces) , L_VC_wallhang (10 pieces) and L_glue (5 pieces). Each batch has a certain probability to be clone as anticipated in the variable setting phase, moreover once the batch has been cloned the next one will have to wait a normally distributed amount of time that should represent the kiln speed setting (in this case normally distribute 9 min with standard deviation 0.25 min).

Once the batch is clone it is sent to the P_storage process where a conveyor belt moves the pieces into a Q_buffer, simulation the movement of the kiln-cart on the automated conveyor.

```
/*Load Batches Generation*/
begin P_start arriving procedure
 while 1=1 do begin
   set V_set to 1
     while V_set <2 do begin
       set A_type to oneof(V_bowls:1,V_FFC_pack:2,V_VC_wallhang:3,V_FFC_glue:4)
       if A_type =1 then clone 6 load to P_storage nlt L_bowls
       if A_type =2 then clone 5 load to P_storage nlt L_FFC_pack
       if A_type =3 then clone 10 load to P_storage nlt L_VC_wallhang
       if A_type =4 then clone 5 load to P_storage nlt L_FFC_glue
       inc V_set by 1
     end
   wait for stream1 n 9, .25 min
 end
end


/* Conveyor Buffer out of Kilns*/
begin P_storage arriving procedure
 move into Q_in
 move into conv.sta_in2
 travel to conv.sta_out2
 move into Q_buffer
 send to P_inspect
end

```

Figure 65, Loads generation and Conveyor Buffer

Inspection Phase

After the conveyor has moved the batch into the Q_buffer the inspection operations begin. One of the two operators is claimed for the inspection process (80% of times R_operator(1) and 20% of times R_operator(2)). During the process depending on the kind of load processed a certain amount of time is needed and finally each piece is sent to one of three different processes depending if the piece is good, to be repaired or to be scrapped. Also, in this case a stochastic distribution is used based on historical data to decide how many pieces will be good or else.

```
/*Inspection Phase*/
begin P_inspect arriving procedure
 set A_index to oneof(80:1,20:2)
 use R_operator(A_index) for 5 sec /*picking from kilncart*/
 move into Q_inspect
 if A_type =1 then use R_operator(A_index) for t 25, 30, 35 sec /*inspecting*/
 else if A_type =2 then use R_operator(A_index) for t 45, 50, 55 sec  /*time depends on
 else if A_type =3 then use R_operator(A_index) for t 40, 45, 50 sec
 else if A_type =4 then use R_operator(A_index) for t 45, 50, 55 sec
 send to oneof(80:P_good,13:P_repair,7:P_scrap)
end

```

Figure 66, Inspection Phase

Scrapping Phase

During this phase the P_scrap begins where the R_operator(1) throws away the damaged piece after having found unpreparable defects during the inspection phase. The scrapped pieces are thrown in a container that gets full with approximately 20 pieces and once full is driven away through a forklift thanks to R_operator(2).

```
/*Scrap Sorting Phase*/
begin P_scrap arriving
 get R_operator(1)
 wait for t 25, 30, 40 sec
 free R_operator(1)
 move into Q_scrap_wait
 if OL_scrap_container current loads is 19 /*the container gets full with aproximately 20
 send to P_scrap_out
 else /*if not full yet, then wait until full*/
 wait to be ordered on OL_scrap_container
end
/*Scrap out*/
begin P_scrap_out arriving
 order 19 loads from OL_scrap_container to die
 get R_operator(2)
 wait for t 35, 45, 50 sec /*take forklift*/
 use R_forklift for e 3 min /*drive forklift empty scrap container*/
 wait for t 35, 45, 50 sec /*park forklift*/
 free R_operator(2)
 send to die
end
```

Figure 67, Scrapping Phase

Repairing Sorting Phase

When the P_repair begins the R_operator(1) positions each piece on a specific pallet depending on its type, the time to move the piece on top of the pallet is triangular distributed and depend on the bulkiness of the piece itself. After the piece has been positioned it will wait on top of the pallet until it gets full. A distinction should be made regarding the FFC models, as a matter of facts those models are stored in the same pallet that has higher capacity than the other (Figure 68).

```
/*Repair Sorting Phase*/
begin P_repair arriving
 get R_operator(1)
 if A_type =1 then wait for t 25, 30, 35 sec /*moving damaged pcs into pallet*/
 else if A_type =2 then wait for t 40, 45, 50 sec /*time depends on bulknes/weight of pcs*/
 else if A_type =3 then wait for t 30, 35, 40 sec
 else if A_type =4 then wait for t 40, 45, 50 sec
 free R_operator(1)
 if A_type = 1 move into Q_repair_wait(A_type)
 else if A_type = 3 move into Q_repair_wait(A_type)
 else if A_type = 2 move into Q_repair_FFC
 else if A_type = 4 move into Q_repair_FFC
 if A_type =1 then send to P_bowl_repair /*sending to next process*/
 else if A_type =2 then send to P_FFC_repair
 else if A_type =3 then send to P_VC_repair
 else if A_type =4 then send to P_FFC_repair
end

/*FFC Repair*/
begin P_FFC_repair arriving
 if OL_FFC_repair current loads is 39
 order 39 loads from OL_FFC_repair to die
 else
 wait to be ordered on OL_FFC_repair
end


/*Bowl repair*/
begin P_bowl_repair arriving
 if OL_bowl_repair current loads is 11
 send to P_repair_out
 else
 wait to be ordered on OL_bowl_repair
end

/*VC repair*/
begin P_VC_repair arriving
 if OL_VC_repair current loads is 15
 send to P_repair_out
 else
 wait to be ordered on OL_VC_repair
end
```

Figure 68, Repair sorting phase

Good Pieces Sorting Phase

Finally, the third sorting phase is addressed when the inspected piece results to be good. Based on the load type R_operator(1) performs a moving operation that last for a triangular distributed time lapse depending on the bulkiness of the piece. Moreover, the good pallets from the wall hanging bowls and the floor standing bowls are positioned on a queue that waits for the AGVs to pick up, this queue is called Q_agv_good. The queue is structure so that once this que achieves three full pallet the are sent to die in order to empty space for the next once, meaning that no actual AGV is modelled in the simulation.

```
/*Good Pieces Sorting Phase*/
begin P_good arriving
 get R_operator(1)
 if A_type =1 then wait for t 10, 15, 17 sec /*moving good pcs into pallet*/
 else if A_type =2 then wait for t 25, 30, 35 sec
 else if A_type =3 then wait for t 25, 30, 35 sec /*time depends on bulknes/weight of pcs*/
 else if A_type =4 then wait for t 15, 20, 25 sec
 free R_operator(1)
 move into Q_good_wait(A_type)
 if A_type =1 then send to P_bowl_out /*sending to next process*/
 else if A_type =3 then send to P_VC_out
 else if A_type =2 then send to P_pack
 else if A_type =4 then send to P_glue
end


/*Bowl and VC pallet fullfilment*/
begin P_bowl_out arriving
 if OL_pallet_bowl current loads is 11
 send to P_agv_good
 else
 wait to be ordered on OL_pallet_bowl
end

begin P_VC_out arriving
 if OL_pallet_VC current loads is 15
 send to P_agv_good
 else
 wait to be ordered on OL_pallet_VC
end


/*Bowls and VC out*/
begin P_agv_good arriving
 if A_type =1 then order all loads from OL_pallet_bowl to die
 if A_type =3 then order all loads from OL_pallet_VC to die
 set load type to L_pallet
 use R_operator(2) for 2 min /*transport pallet in target position and take new pallet in old spot*/
 move into Q_agv_good
 if OL_agv_good current loads is 3
 order 3 loads from OL_agv_good to die
 else
 wait to be ordered on OL_agv_good
end
```

Figure 69, good pieces sorting phase

FFC Gluing Packaging Phase

Part of the good pieces are sent to the gluing station where the R_operator(2) performs the packaging operations with the help of the station. Once enough pieces are packaged the full pallet is sent to the P_wrap process where the pallet is wrapped.

```
/*Gluing FFC CURRENT*/
begin P_glue arriving
 get R_operator(2)
 wait for t 25, 30, 35 sec /*load and pre-package*/
 use R_glue for 15 sec
 wait for t 25, 30, 35 sec /*unload*/
 free R_operator(2)
 move into Q_glue_out
 if OL_pallet1 current loads is 7 /*if 7 parts are already in the order list then the 8th one makes a full pallet*/
 send to P_wrap
 else /*more parts needed to fill the pallet*/
 wait to be ordered on OL_pallet1
end
```

Figure 70, Gluing FFC Current

FFC Packaging Phase

Once the P_pack process begins, all the loads stored in the pallet are moved by R_operator(2) in the packaging station where P_final_pack begins. During this next process both the operators are involved in material handling and manual packaging of the pieces. When enough pieces are packaged the pallet is full and is sent to the P_wrap process, where the wrapping operation is performed.

```
/*Packaging FFC CURRENT*/
begin P_pack arriving procedure
 if OL_pack current loads is 11 /*if 11 parts are already in the order list then the 12th one makes a full cart*/
  begin
   get R_operator(2)
   order 11 loads from OL_pack to P_final_pack
   wait for e V_extra min /*moving the cart to the packaging area*/
   free R_operator(2)
   send to P_final_pack
  end
 else
 wait to be ordered on OL_pack
end

begin P_final_pack arriving
 move into Q_input_pack
 get R_operator(1)
 get R_operator(2)
 wait for t 5, 10, 15 sec
 use R_pack_station for e V_pack min
 wait for t 5, 10, 15 sec
 free R_operator(1)
 free R_operator(2)
 move into Q_output_pack
 if OL_output_pack current loads is 7 /*if 7 parts are already in the order list then the 8th one makes a full pallet*/
 send to P_wrap
 else /*more parts needed to fill the pallet*/
 wait to be ordered on OL_output_pack
end
```

Figure 71, FFC packaging phase

Wrapping Phase

During this last phase the FFC pallets coming from P_glue and P_final_pack are inserted in the wrapping machine by the R_operator(2) and once wrapped the load is sent to die.

```
/*Wrapping Phase*/
begin P_wrap arriving procedure
 if A_type =2 then order all loads from OL_output_pack to die
 if A_type =4 then order all loads from OL_pallet1 to die
 set load type to L_pallet
 use R_operator(2) for 30 sec /*transport pallet in target position*/
 move into Q_wrap
 get R_operator(2)
 wait for t 25, 30, 35 sec /*loading of pallet*/
 use R_wrap for 1 min /*wrapping operation*/
 wait for t 25, 30, 35 sec /*unloading of pallet*/
 free R_operator(2)
 send to die
end
```

Figure 72, Wrapping phase

Operator's Downtime and Breaks

The load L_dummy that we defined at the beginning of this sub-chapter is sent to this P_break process where a loop is continuously repeating throughout the whole length of the process. In this loop both the resources are taken down for 20 min every 2 hours and half in order to simulate the breaks and the shift changes during daily operations.

```

/*Operator Breaks and downtimes*/
begin P_break arriving
  while 1=1 do begin
  wait for 150 min
  take down R_operator(1)
  take down R_operator(2)
  wait for 20 min
  bring up R_operator(1)
  bring up R_operator(2)
 end

end


```

Figure 73, Operator's break and downtimes

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