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Material flow analysis and human resources allocation regarding heavy weight lifting: A case study from a gas bottle preparation unit

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Material flow analysis and human resources allocation regarding heavy weight lifting: A case study from a gas bottle preparation unit

Submitted to obtain the Degree of Master in Industrial Engineering and Management.

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Let the future tell the truth, and evaluate each one according to his
work and accomplishments. The present is theirs; the future, for
which I have really worked, is mine.
Nikola Tesla

To my parents

ACKNOWLEDGEMENTS

I would like to start expressing my great appreciation to all my advisors: In Portugal, Professor Cristóvão Silva and Professor Pedro Coelho, and in France, Professor Nathalie Klement who welcomed and treated me like I was a student of her own.

Also to Air Liquide for trusting me this important task, especially to Remi who provided me essential data without which it would not have been possible to complete my work.

To my friends in Portugal, for all the unforgettable moments. To my new friends in France, for making me feel like home. I won’t forget you.

Finally, I wish to thank my family, especially my parents, for all the effort and sacrifice. You are the reason I’m here today.

ABSTRACT

This thesis reports the consulting work carried out during an externship on a gas bottle preparation unit of Air Liquide, in France, regarding multiple aspects of their production process. The whole material flow was modeled, then a study on the allocation of workers regarding weight lifting was made, followed by an investigation of different production scenarios and layout proposals.

To model the industrial process, Discrete Event Simulation was used, retrieving valuable information about the performance of their equipment, processes, and the factory as a whole. Concerning the allocation of workers: Mathematical Formulation, Constructive Heuristics and Genetic Algorithms were implemented, with the purpose of balancing the weight lifted by different workers. To evaluate different Production Scenarios, the simulation model and the heuristics developed before were used to get comparison indicators. At last, different Layout proposals were selected aiming the decrease on the distance that bottles go through from the moment they enter the system until they leave the facility.

With the methodology described above, results showed that the balance between the weights lifted by different workers can be improved up to 85%, and the distance that each bottle go through can be decreased up to 25%, comparing to the current situation. Opportunities for future work were also identified, opening doors to new investigations and further studies on the subjects here discussed.

Keywords Discrete Event Simulation, Multi-Objective Problem, Genetic Algorithm, Weight Lifting, Worker Allocation

ABSTRACT – Portuguese Translation

Este documento reporta o trabalho de consultadoria levado a cabo durante um estágio não residente, realizado numa unidade de preparação de garrafas de gás chamada *Air Liquide*, em França, relativo a múltiplos aspetos do seu processo produtivo. O fluxo de materiais foi simulado, seguido dum estudo da alocação dos funcionários de acordo com a movimentação de cargas pesadas, de uma análise de diferentes cenários produtivos e de propostas de *layout*.

Para simular o processo industrial, recorreu-se à técnica de Simulação por Eventos Discretos, que permitiu recolher valiosas informações acerca da performance dos equipamentos, processos e da fábrica como um todo. Relativamente à alocação dos colaboradores foram utilizadas técnicas como Formulação Matemática, Heurísticas Construtivas e Algoritmos Genéticos, no sentido de equilibrar o levantamento de pesos. Para avaliar os diferentes cenários produtivos, o modelo de simulação e as heurísticas referidas anteriormente foram utilizados para obter indicadores de comparação. Por fim, foram propostos diferentes Layouts com o objetivo de diminuir a distância que as garrafas percorrem desde o momento que entram nas instalações até ao momento da sua saída.

Com estas metodologias, demonstrou-se, por exemplo, que o equilibro de pesos levantados pelos diferentes colaboradores pode melhorar em até 85%, e que a distância percorrida por cada garrafa pode diminuir em 25%, comparando com os valores atuais. Foram também identificadas oportunidades de trabalho futuro, abrindo portas para novas investigações ou estudos mais específicos sobre os tópicos abordados.

Palavras-Chave Simulação por Eventos Discretos, Problemas Muti-Objetivo, Algoritmo Genético, Movimentação de cargas pesadas, Alocação de Recursos

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SYMBOLS AND ACRONYMS

Symbols

H – Horizontal location of the object relative to the body

V – Vertical location of the object relative to the floor

D – Distance the object is moved vertically

A – Asymmetry angle or twisting requirement

F – Frequency and duration of lifting activity

C – Coupling or quality of the workers grip on the object

ג – Weight given to a certain objective function [0,1]

∀ - For all

Acronyms

CX – Cycle Crossover

KPI – Key Performance Indicators

NIOSH – National Institute of Operational Safety and Health

NWOX – Non-Wrapping Ordered Crossover

OX – Ordered Crossover

PDF – Probability Density Function

PMX – Partially-Mapped Crossover

UPMX – Uniform Partially-Mapped Crossover

VSM – Value Stream Mapping

1. INTRODUCTION

This master thesis is a result of a collaboration between the University of Coimbra and a French Engineering School "*École Nationale Supérieure d'Arts et Métiers*", as a part of a larger project between the last and Air Liquide, a multinational company in the field of industrial gases. The purpose of the study was to first understand the flow of material and human resources in their industrial site, by building a virtual model that would represent all major activities, and then to make result based suggestions to meet the company desires. Those are:

- Decrease the physical effort required from workers;
- Improve the Facility's Layout;
- Increase Productivity;
- Reduce Costs;

With the results from this study, it will be easier for the company to evaluate future investments in the improvement and modernization of the industrial site, as much as for the mechanical engineers that will design and incorporate new technological solutions.

1.1. Business Context

This unit's business core is to transform empty metal bottles into bottles that are ready to be filled with acetylene **[Figure 1.1].** This implies, among other activities, filling them with a porous mass, painting, inserting caps (*chapeau*), valves, and removing the oxygen. More details about the process will be given below.

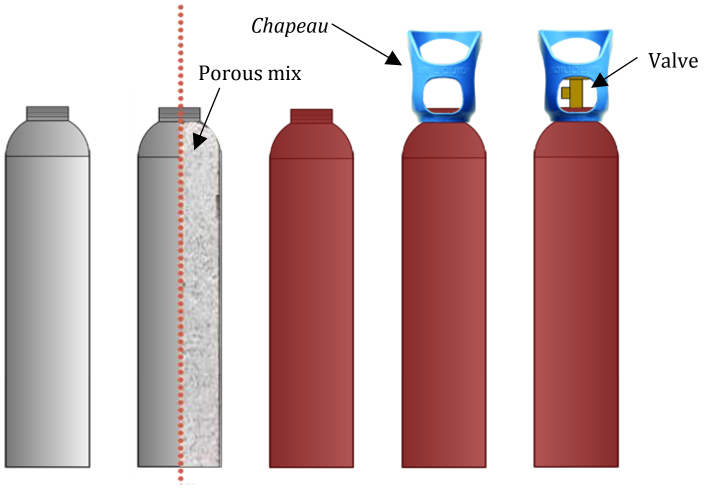


Figure 1.1 - Different visual phases bottles go through

Due to a decrease on the demand over the years (caused in part by the global crisis) Air Liquide has been reducing the number of workers in production, which now comes to 6 (as a promise to the employees, this number will not decrease in the future, regardless of this project's outcomes). Despite of having capacity to produce 60.000

bottles a year, they've been producing less than 50% over the years, fulfilling all the orders that arrive on a monthly basis.

Having already mastered the chemical process, the production itself is still quite rudimental, with almost every activity requiring manual labor. A lot of physical effort is required from the workers, who are getting associated health disorders. Also, the production schedule and the workers allocation is managed by experience and without a systematic method.

1.2. Structure

Because of the fact this thesis aims to be a response to an industrial project, all the company's requests had to be fulfilled. This meant dealing with multiple topics instead of just one. Therefore, and to facilitate the reading of this report, theoretical backgrounds of each subject will be described in its respective document's section.

The different topics will be presented in the order by which they were analyzed during the period of the externship, as **Figure 1.2** suggests.

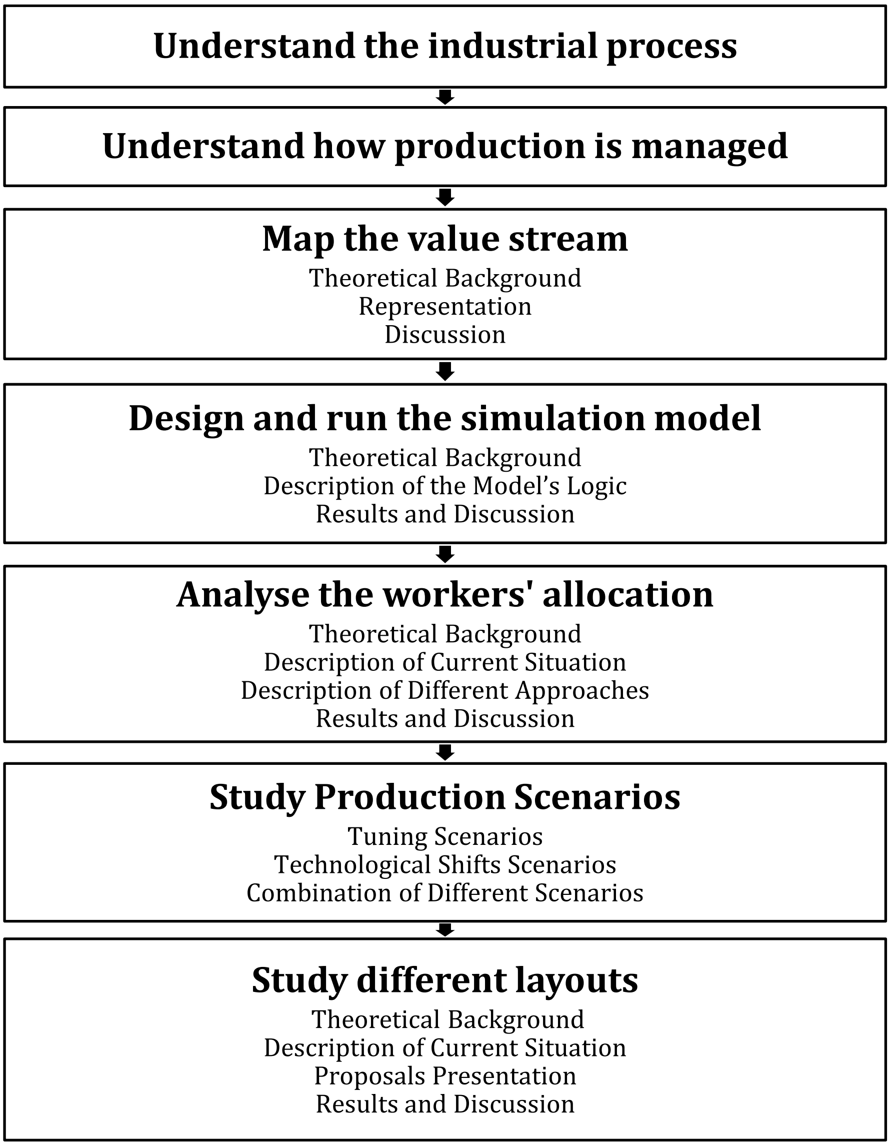


Figure 1.2 - Flowchart of the report's structure

2. INDUSTRIAL PROCESS

As far as this particular industrial process is concerned **[Figure 2.1],** the chain of events starts with the arrival of empty metal bottles at the unit which are stocked outside in wooden pallets. It is considered that, at a certain time, there's enough stock of these to prevent production from running out of raw material.

Inside the industrial site, we can say that, the process itself has 3 main material flows: The Bottle's flow, the "Porous Mix" (used to fill the empty bottles) and the "Bouchon" (which is a kind of bottle cover to use inside the furnaces). A general explanation will be given about the major activities of each flow in **Section 2.1**.

At the end, the product, ready to be filled with acetylene, is packed in pallets and shipped by truck to other facilities, before meeting the final costumer.

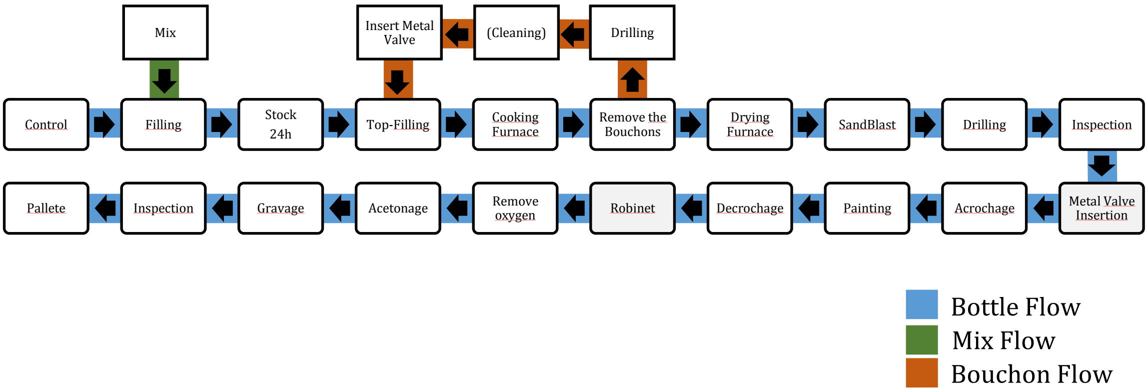


Figure 2.1 - Fluxogram of the different main activities

Because it gathers most of the activities and represents the majority of the process, the material flow that will be mostly discussed in the document is the Bottle's flow. **Figure 2.2** represents a 3D scheme of it, to help giving an overall picture of the different activities implied.

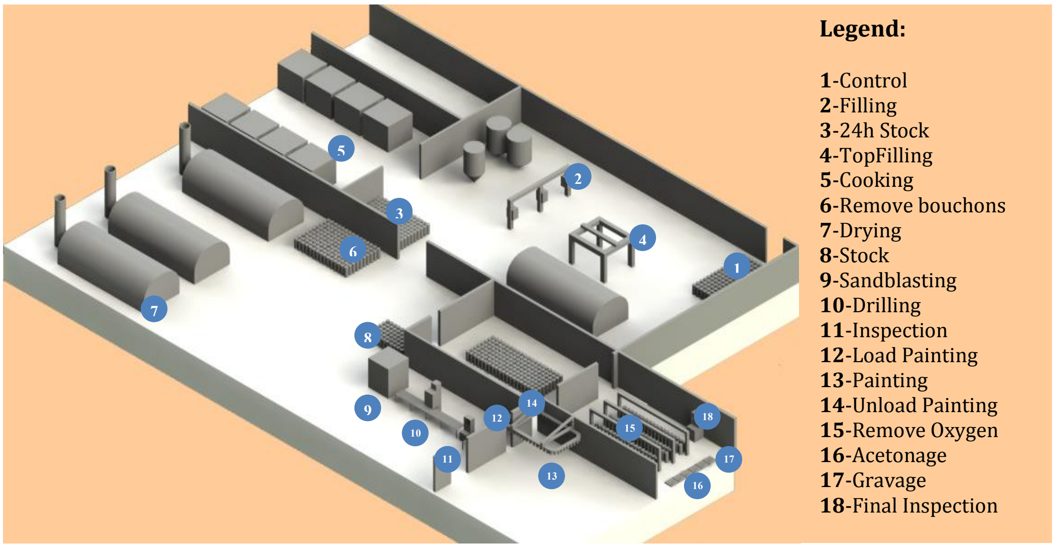


Figure 2.2 - 3D scheme of the industrial unit (legends below)

2.1. Bottle Flow

Control [1] -The first activity bottles go through. An operator controls each bottle one by one and puts them aside. The purpose of this activity is to make sure there's no defects coming from the supplier. For each batch there is a special type of test that is done to only 3 bottles. (1 worker)

(Bottles coming from the control station are transported to the next activity, at the end of each day, outside the regular working schedule.)

Filling [2] -Consists on filling each bottle with a porous mix that is already in a container (further explanation will be given about how the mix is done **[see explanation2]**). There are three of these stations which means it's possible to fill three bottles at the same time. One worker loads the stations with empty bottles and another one unloads them when finished. After a batch is completed, they are wrapped with a metal string and moved to a "24h Stock Area". (2 workers)

24h Stock Area [3]- A batch must remain here until the next day before getting Top-Filled (next activity). The reason for this is to let the water get out of the liquid mix.

Top-Filling [4]- Bottles are filled again (until the top), one by one, using the same kind of mix. A "Bouchon" **[see explanation3]** is then inserted before sending them to the "Cooking Furnace". After each batch is completed, it's transported to a "Cooking Furnace". (2 workers)

Cooking Furnace [5]- There are 8 Furnaces. Depending on the bottle's size, each one can fit 4 batches (of 3.35L, 5.8L and 9.8L) or 2 batches (22L). There's a minimum time for a batch to be in the Furnace of 48h, but there is no maximum. That's why they insert a new batch to an already working Furnace if there is still space left.

(Bottles remain in the "Cooking Furnaces" even after finished, until the day there are enough to fill the "Drying Furnace" [another activity which will be explained below]. When that day comes, they are taken to the next station.)

Removing the "Bouchons" [6]- When bottles arrive this station, they have their metal valves and "Bouchons" removed (by this order) and putted in a container, individually. Every batch is then moved to a "Drying Furnace" until it gets full. (2 workers)

Drying Furnace [7]- This activity is the most energy consuming. That is why production managers wait until they are full to start the operation. They can fit 20 batches of 3.35L, 5.8L and 9.8L bottles, and 10 batches of the 22L ones. Due to the low demand, they are using just one of this Furnaces, despite having 4. It takes 5 days to complete the drying process.

(After the process is complete, all batches are transported to another "Stock Area" [8] where they remain until needed in the next activity.)

Sand Blasting [9]-A support needs to be inserted in every bottle to enable them to be sandblasted. The same worker who does that, inserts batches of 12 bottles (of 3.35L and 5.8L) or 9 bottles (of 9.8L) in the sandblasting machine. (1 worker)

Drilling [10]- A drill in the dry porous mass needs to be done to every bottle. There's a semi-automatic machine, but the worker responsible for the Sandblaster needs to do the loading and unloading. (1 worker)

Inspection [11]- The worker responsible for this task has to inspect each bottle and register its unique ID in the system. (1 worker)

Painting the Top [12]- Paint the top of the bottle with a painting brush. (1 worker)

Metal Valve Insertion [12] (1st alternative activity)- Depending on the bottle, some get a metal valve installed between inspection and the next station. (1 worker)

Loading bottles into "Painting Conveyor" (Acrochage) [12]- A worker is responsible for loading each bottle (with the help of a machine) in the "Painting Conveyor". (1 worker)

Painting [13]- Despite the loading and unloading being manual, the painting process itself is automatic. The bottles are painted while they pass through the conveyor. It has a capacity of 84 units, regardless of their weight.

Insert sticker [14]- The same worker responsible for unloading the bottles, needs to insert a sticker to it. (1 worker)

Unloading bottles from "Painting Conveyor" (Decrochage) [14]- A worker is responsible for unloading the bottles and inserting a blue plastic cap **[see Figure 1.1]** called "chapeau". (1 worker)

Metal Valve Insertion (2nd alternative activity)- Bottles which didn't get the metal valve before, are transported to this station by chariots (with capacity for 10 bottles). Then, individually, they get there metal valves inserted and putted back in the chariot. After all are completed, they are transported to the next station. (1 worker)

Removing the Oxygen [15]- Bottles remain in this area (inside the chariots) while they have oxygen removed from the inside. This activity's capacity is 80 units.

Acetonage [16]- It's a process of inserting a small amount of Acetone in each bottle. There are 6 parallel machines that do it automatically but need to be loaded and unloaded manually. (1 worker)

Engraving [17]- A manual process of engraving the bottles with a hammer for identification purposes. (1 worker)

(A worker loads the "Acetonage Machines" with 6 bottles, and puts them back in the chariot when completed to be engraved. Every time he removes one bottle from a machine, he replaces it for a new one immediately.)

Inspection [18]- Units are inspected individually before being pelletized and shipped. (1 worker)

2.2. Mix Flow

This section concerns the flow of the porous mix used in the industrial process. When there is a need to make the mix, a worker arrives 1 hour earlier in the morning to avoid making the other workers wait.

Mixing Containers- There are two mixing containers. The process of mixing itself is automatic, but the containers need to be fed with the raw materials manually.

Intermediate Container- It's the container from which the bottles are filled. When the intermediate container is empty (in the beginning of the day), the operator uses both mixing containers. After that, he transfers the content of one of them to the intermediate container, and from that moment forward he starts to operate each mixing container alternately. There must be always mix in the intermediate container while the "Filling Activity" is operating.

At the end of the day, they separate a portion of the mix to a different container in order to supply the "Top-Filling Activity". This is to make sure they use the same mix for Filling and Top-Filling for each bottle.

2.3. Bouchons Flow

The purpose of this section is to explain the flow of the "bouchons" **[Figure 2.3]**. After being removed from the bottles (which happens before "Drying Furnace)", they are dirty and they have remains of dry mix inside.

In order to make them usable again, they go through three activities, all of which require manual labor:

Drilling- A drilling machine is used to remove dry mix from the inside of the "bouchons".

Cleaning- After some time they get dirty on the outside so they need to be cleaned. This activity occurs only when needed.

Metal valve assembly- Insert a metal valve again.

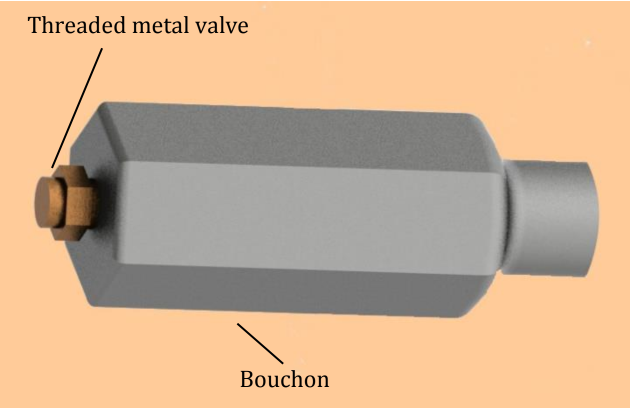


Figure 2.3 – 3D representation of the bottle's metal cover called "Bouchon"

3. INDUSTRIAL MANAGEMENT

As explained earlier in the Introduction, Air Liquide produces the bottles according to monthly orders. Because the most expensive activity in the unit is Drying, the entire production schedule is done so that every time the Furnace is working, it's on its full capacity. This means that, if at a particular time there is an order smaller than what the Furnace can fit, they will produce more than needed in order to fulfil it. This causes some unnecessary stock in the industrial site, but also gives them more capacity to deal with unexpected changes in the normal behavior of the value chain.

Also, as mentioned before, due to a recent low demand, the number of employees has been decreasing over the years. This means a higher complexity in the workers allocation, since there are a lot more activities than human resources. For that reason, there's no continuous flow of products. Activities don't run every days and employees are allocated in different stations accordingly. The way the company handled this situation was to assign workers in different jobs, every day **[Table 3.1]**.

The activities are divided into two major groups. The ones before the Drying, and the ones after. Below there's a three week example of what usually happens in terms of scheduling. In the first two weeks there's control, which means that the first group of activities will run (the remaining workers of each day are used in second group activities, finishing dried bottles in stock), and in the other two weeks, only second group activities will be running, to finish the bottles dried before.

Table 3.1 - Example of week schedule

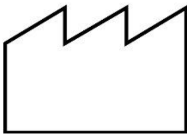
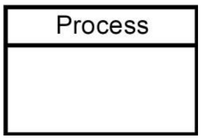
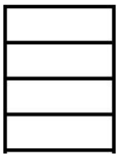
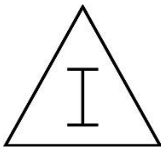
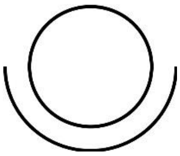
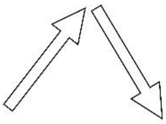
Activity	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F
Control			■	■						■	■																	
Mixing				■	■	■					■	■	■															
Filling				■	■	■					■	■	■															
				■	■	■					■	■	■															
Top filling					■	■	■					■	■	■														
					■	■	■					■	■	■														
Suplying Fournace										■							■											
										■							■											
Finishing										■				■			■	■	■	■	■			■	■	■	■	■
										■				■			■	■	■	■	■			■	■	■	■	■
										■				■			■	■	■	■	■			■	■	■	■	■
										■				■			■	■	■	■	■			■	■	■	■	■
Acetonage			■	■			■											■	■	■	■			■	■	■	■	■
			■	■			■											■	■	■	■			■	■	■	■	■
Drilling			■	■	■	■	■			■	■	■	■															
Cleaning			■																									
Other			■				■				■																	

4. VALUE STREAM MAPPING

Value Stream Mapping is a Lean Manufacturing tool that allows to represent the flow of materials and information of a particular process (which can be industrial or not). It gives an overall picture of it and can help identifying delays, excessive inventory and the bottlenecks of the system (Ar, 2012).

Details about the different symbols used in these kind of tool can be found in (Rother & Shook, 2003). The ones addressed in this document are presented below in **Table 4.1**:

Table 4.1 - VSM symbols

Symbol	Description	Symbol	Description
	Supplier or Costumer		Dedicated process
	Data box		Inventory
	Human Resource		Shipments
	Electronical information		Timeline

According to (Gahagan, 2012) , the VSM approach has 3 main steps. The first is to produce a diagram that shows the current material and information flow (called Current State Map), usually created while walking down the production line. The second is to build a Future State Map with the identified improvement opportunities discovered in the first step. The last is to carry out the improvements, implementing action plans.

In this document, only the Current State Map is addressed **[Figure 4.1]**, used to assist on the creation of the simulation model described in the following section. It gathers all information about the process such as processing times, number of workers and batching volume. The availability was considered to be 100% on all activities. The purpose of the second step was fulfilled in the Scenario Section of the document, where different improvement proposals were analyzed.

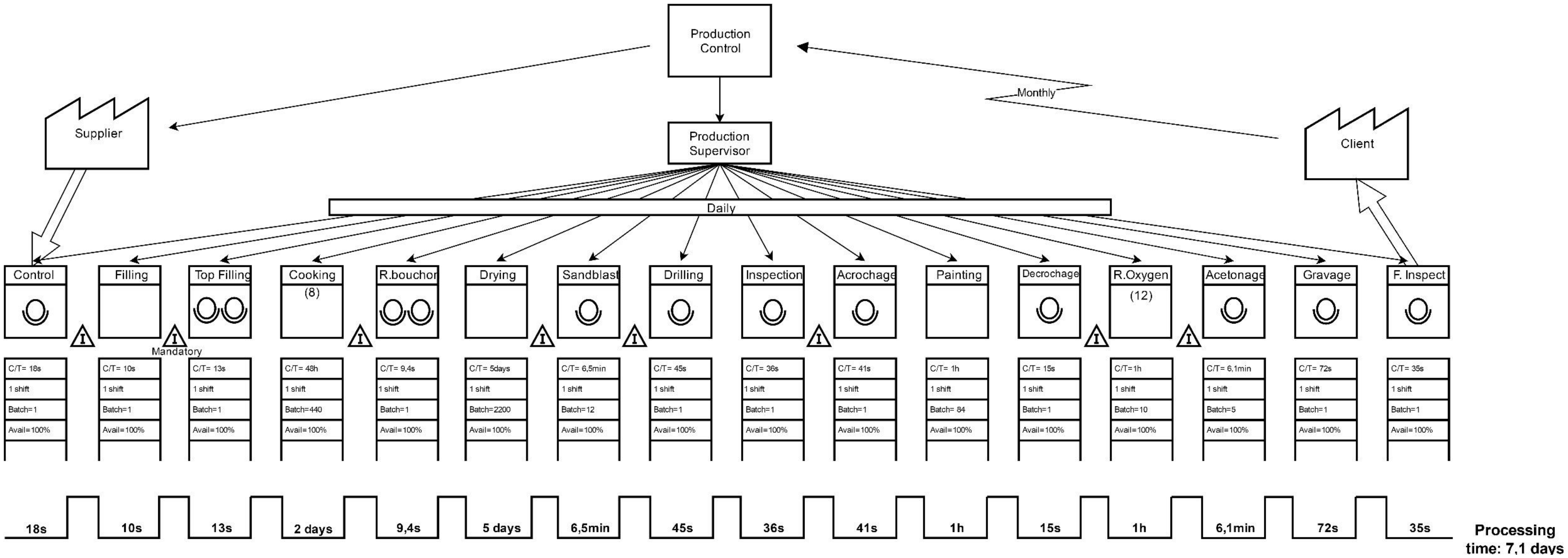


Figure 4.1 - Visual Stream Mapping

Due to the large number of activities implied in this process, only the most significant ones are represented. This means that some minor activities might have their process times included in the larger ones. Although, this Visual Stream Map is currently incomplete. The waiting times and stock levels are not represented and must be collected inside the company. Using the simulation results to fill them could be a possibility but would go against the whole concept of the method (which could be, eventually, used to further validate the simulation).

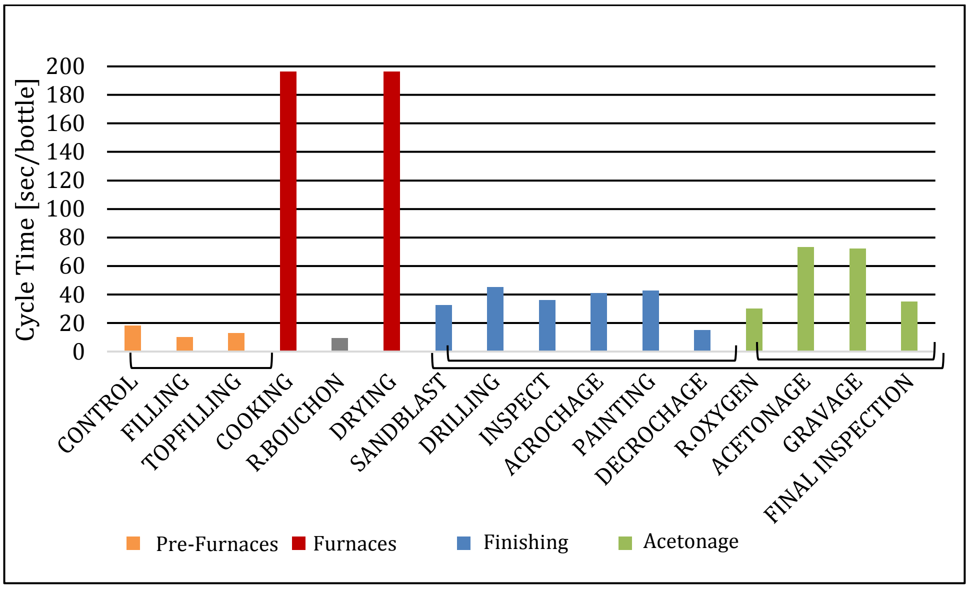


Figure 4.2 - Unit Cycle-Time for activities in VSM

As can be seen in **Figure 4.2,** there are two main identified bottlenecks in the system: the furnaces. Although the Cooking ones have smaller cycle-times than the Drying, the current scheduling makes the Cooking of 20 batches to take the same time as Drying.

Having this into account, the remaining activities are separated in the chart, into two main groups: before furnaces and after furnaces. The second group, due to the nature of the activities was also separated before and after Decrochage. We can detect as being the bottlenecks of the blue and green groups, the Drilling and Acetonage/Gravage, respectively.

5. SIMULATION

5.1. Theoretical Background on Simulation

The chosen technique to study the flows of this industrial site was Discrete Event Simulation. This kind of tool had been widely used over the years in multiple contexts in order to replicate real world systems and analyze possible changes. Although the method itself do not allow to do optimization, it can help studying "What If" scenarios by showing interesting Key Performance Indicators (KPI) for each (Banks et al., 2005).

Shannon (1998) defines simulation as being the process of designing a model of a real system and conducting experiments with it for the purpose of understanding the behavior of the current system and evaluating various future strategies for its operation. According to (Jašek et al., 2016) the relationship between real objects, systems and models can be described by **Figure 5.1**.

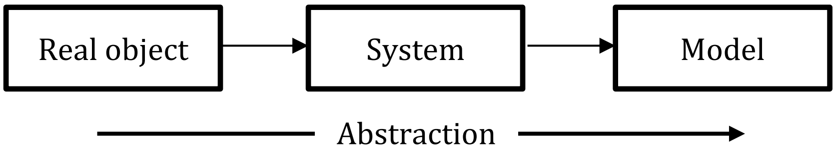
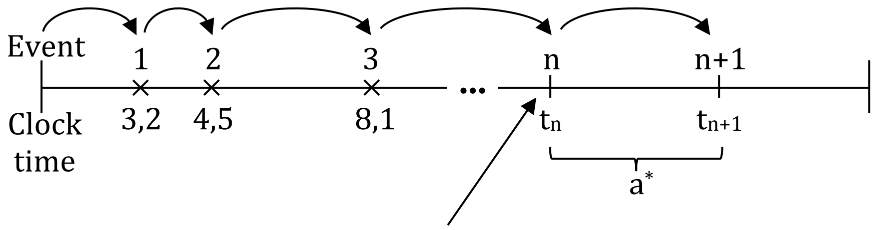


Figure 5.1 - Relationship between real objects, systems and models

Concerning how time is handled, Discrete-event Simulation differs from Continuous Simulation in the way that the system can change at only a countable number of points in time. Those points represent the instant when a certain event occurs (Law, 2008). These events can represent the arrival of some work item, the start of some process, or any other situation that makes the system change. Further explanation about how time advances in the simulation models is represented in the **Figure 5.2**, below:



At simulation time t_n (assumed to be the instant of the n^{th} event), interval a* is calculated and $t_{n+1}=t_n+a^*$ is scheduled.

Figure 5.2 - Timeline in a Discrete Event Simulation (Adapted from (Banks et al., 2005))

When the last event occurs, it's time to gather the results relative to the entire duration of the run **[last step of Figure 5.3]**. Custom result reports can include minimum, maximum and average stock levels, durations, occupation rates, and other important KPI to analyze the flow of the process.

Regardless of the simulation software, there are some parameters that need to be defined before trying to obtain any result from this kinds of tool. Those are the Run Time (length of time during which the simulation will run), Number of Runs (number of times the simulation will run, in order to gather statistical valid conclusions), and Warm-up Period (period of time to establish normality in the system, during which results will not be collected) (Banks et al., 2005).

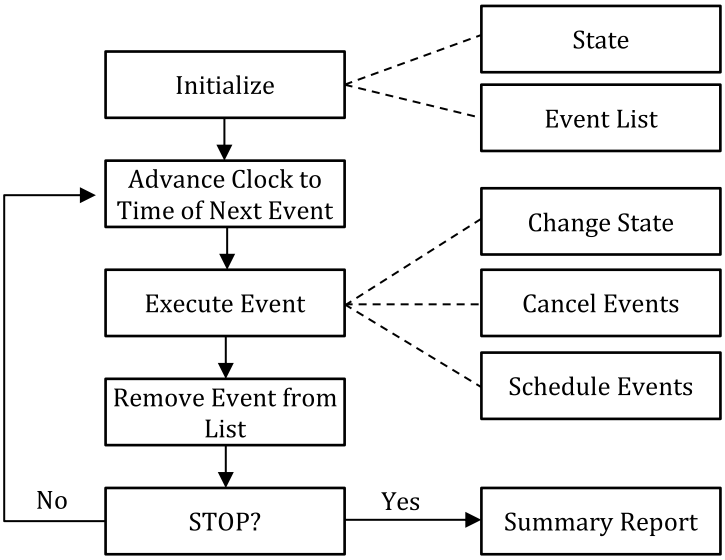


Figure 5.3 - Discrete event simulation (Adapted from Laguna & Marklund, 2005)

There are multiple **advantages** on using Simulation Softwares. Shannon (1998) gathers the most important ones, presented below:

- Test new designs, layouts without committing resources to their implementation;
- Identify bottlenecks in information, material and product flow. Test options for increasing the flow rates;
- Test hypothesis about how or why certain phenomena happens in the system;
- Gain a better insight about which variables are most important to performance;

Despite having a great amount of strengths, it has, off course, some **disadvantages**:

- It requires specialized training;
- Gathering the input data can be time consuming and not always leads to unquestionable results;
- They do not lead to an optimal solution. They can only show the behavior under the conditions specified by the user.

A good way to conduct a simulation study (and the way this particular problem was handled) is to follow the seven steps presented in the **Figure 5.4** below. Meetings with the company were held and intermediate reports were sent during the process in order to validate the simulation, which is essential to the credibility of the results (point nº5).

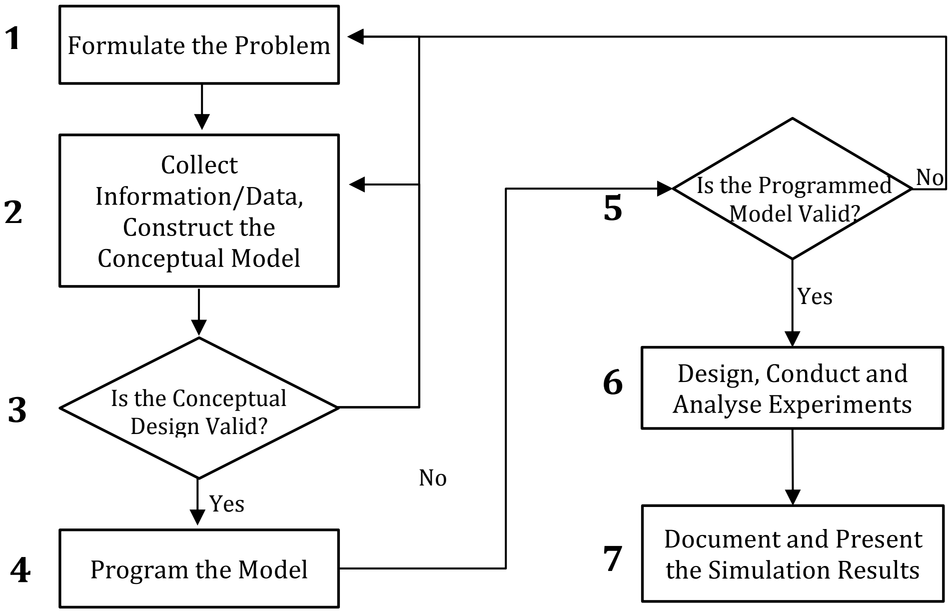


Figure 5.4 - Seven- Step approach for conducting a successful simulation study (Law, 2008)

5.2. Selecting Input Probability Distributions

In the real world there's plenty of uncertainty. Dealing with it the right way, is one of the most important aspects when solving real business problems. It means recognizing that uncertainty exists and using quantitative methods to model it (Albright et al., 2011).

Simulation softwares are able to take into account the existing variability by allowing Probability Distributions to be inserted as input. This is especially important in this particular case study since production is mainly manual and subject to the "human factor". Inserting historical data of the processing times would not be reasonable since the objective is to simulate a large period of time (greater than the available data) and make several runs to draw statistically valid conclusions.

5.2.1. Probability Density Functions

Probability Density Functions (PDF) represent the likelihood that the random variable would be close to a given value. Despite the probability of being a given value is zero, the probability that X takes on a value inside some interval [a,b] is the area under the density function from a to b **[Figure 5.5]**.

$$P(a \leq X \leq b) = \int_{a}^{b} f(x)\, dx \;\; \forall \; a < b \tag{5.1}$$

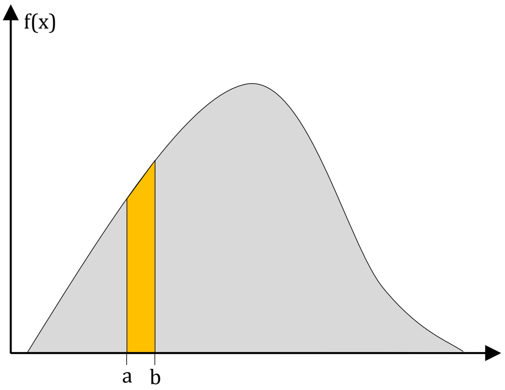


Figure 5.5- Example of Probability Density Function

A PDF must satisfy two conditions:

(i) $f(x) \geq 0 \ \forall \ x$

(ii) $\int f(x)\,dx = 1$

For the purposes of this case study, probability density functions have a lower bound of 0 since they will be used to represent processing times, which cannot be negative.

5.2.2. Methodology used

In order to model random inputs in the simulation, there are plenty of probability distributions from which to choose. To help this process, multiple softwares are available online that can provide clear answers about how different distributions fit our data. One example, with a "student free version", is EasyFit. It was the software used in this study.

Having historical data as input, the software presents the best parameters of a large number of distributions and then allows the user to sort them with a feature called "Godness of Fit" **[Figure 5.6]**. It describes how well each one fits the observations, recurring to three different possible tests: "Kolmogorov–Smirnov", "Anderson Darling" and "Chi-Squared". The one used in this document is the "Kolmogorov-Smirnov". As **Figure 5.6 [B]** suggests, it tests the maximum distance between the observed data and the value expected from the respective Cumulative distribution Function (Frank & Jr, 1951).

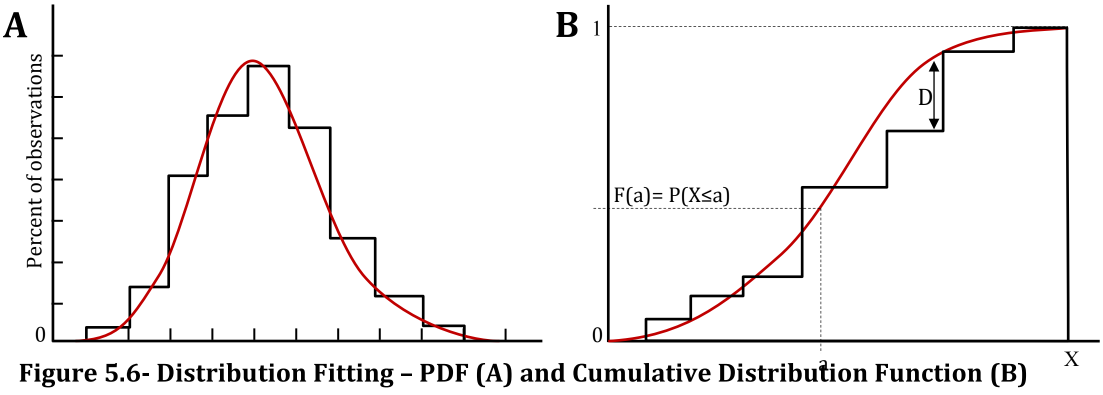


Figure 5.6- Distribution Fitting – PDF (A) and Cumulative Distribution Function (B)

After getting results from *EasyFit*, the best distribution (supported by the simulation software) was chosen for each activity of the industrial process **[Figure 5.7]**.

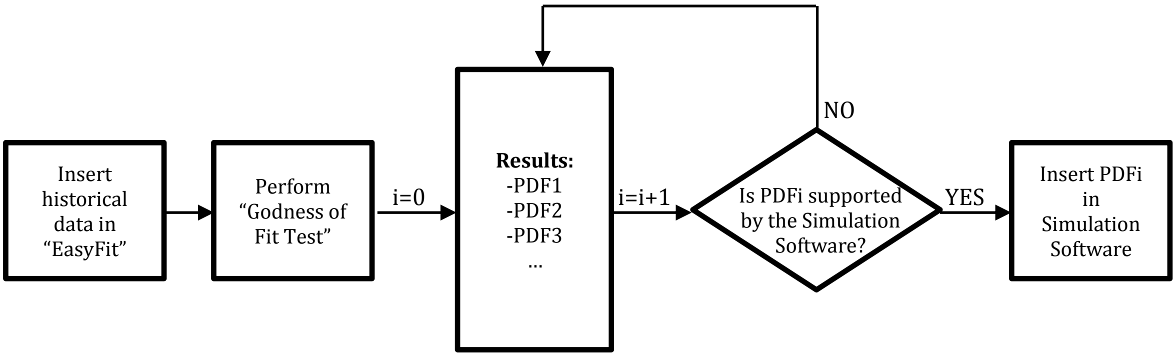


Figure 5.7- Methodology on the Selection of the PDF

5.3. Software

The software used to simulate the industrial unit is called SIMUL8. It allows the user to replicate complex systems using different types of entities **[Figure 5.8]**. It differs from other discrete event simulation softwares by being more intuitive and user friendly.

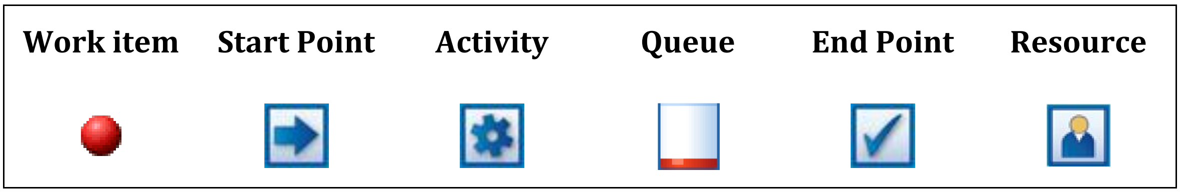


Figure 5.8- Different entities in the software

The model described in this document will not use the same images presented above. While the logic is the same, custom images are used instead to mimic more precisely the factory layout and give a better understanding. The plant of the industrial unit can be inserted as background of the model, and virtual equipment can be placed on top of it. This becomes very helpful when presenting the model to the company or someone that's not familiar with the software because it's easier to associate the virtual model to the real-world process, increasing the credibility towards the company's stakeholders.

Although the software itself has a lot of functionalities and pre-built functions that fit most cases, the user is also allowed to create and insert his own logic functions using a programing language called "Visual Logic" and associate "Label variables" to work-items, which can be used to store any kind of numerical or string based characteristic (ex: weight, serial number, release date, etc).

5.4. Model Layout

The Following image shows the visual part of the simulation. While running the software it's possible to get an animated view of the products and workers moving through the shop-floor over time.

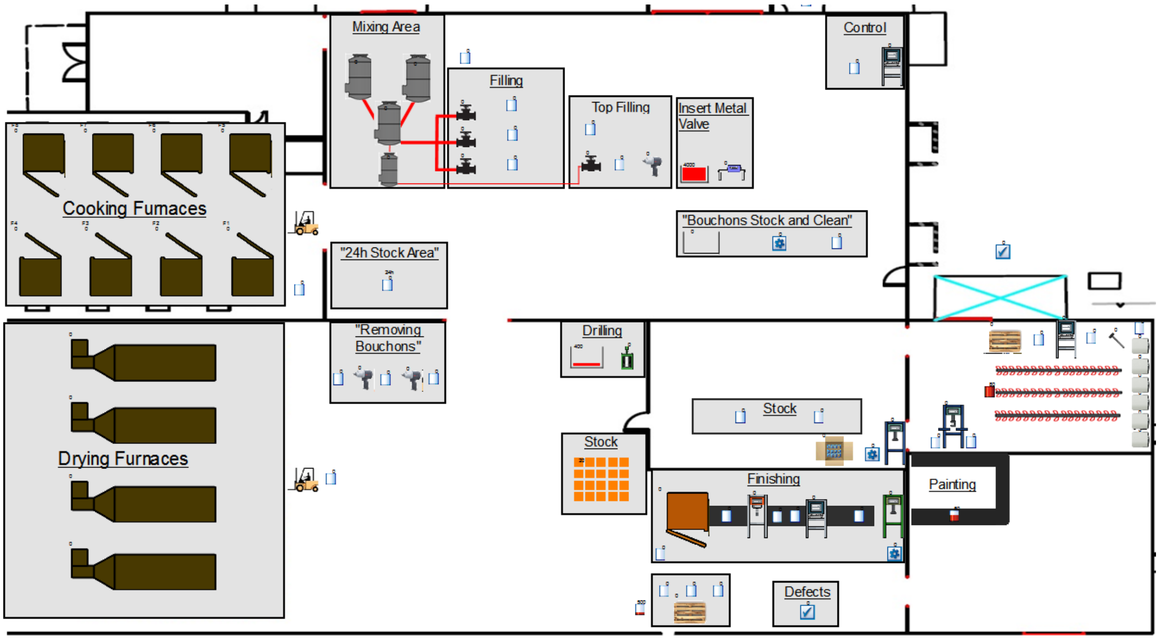


Figure 5.9 - Visual layout of the simulation

5.5. Assumptions

Real world problems are very complex, even when they don't look like. There are so many variables in stake that it would be impossible to perform a simulation without some kind of simplifications. The most important ones taken into account when building the model will be given below:

- Only 3 types of bottles are being considered (3.35L, 5.8L, 9.6L), although the simulation model is prepared to deal with all of them.
- Processing times are the same for all of them. (Data was collected on the 5.8L)
- Stock of empty bottles, valves and blue plastic caps is considered to be infinite.
- Stock of bouchons is much higher than reality (this is to make sure that Top-filling activity doesn't get stuck because of the lack of bouchons).
- Assume that everything is made to get the drying furnace full.
- Every time bottles are removed from the "Removing the Oxygen area", they are replaced with new ones, pulled from the stock.
- There are always 2 workers in Filling.

5.6. Overview on the model's logic

The following topics will show how some of the Process Logics were implemented in order to best represent Air Liquide's industrial process and to explain the simulation in case of future needs:

Mixing Logic

A routine is made every time there's a change in one of the containers. It counts constantly how many of them are empty and when that number reaches 1, the worker stops mixing. In the beginning of the day, as all of them are empty, he mixes two at the same time. Regarding the Top-Filling container, it is filled at the end of the day, with the remaining mix left in the intermediate one.

Cooking Furnaces Logic (dealing with the furnace capacity)

As described before, the number of batches each Furnace can fit depends on the Type of Bottle. The 3.35L, 5.8L and 9.8L can have 4 batches fitted in, but the 22L can only have 2. There's a feature called "Batching based on the total value of a Label" which serves perfectly this purpose. By creating a label with value 1 in the smallest bottles, and with value 2 in the biggest, and by limiting the "total value" of the label to be 4:

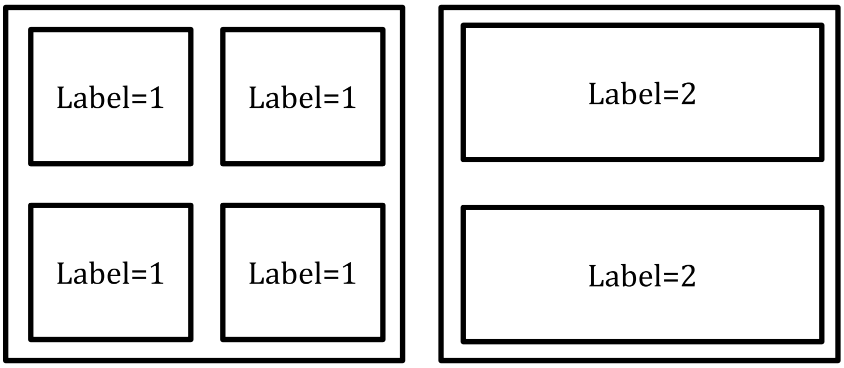


Figure 5.10- Volume fitting logic

3.35, 5.8L, 9.6L bottles:1+1+1+1=4 (fit four batches)

22L bottles: 2+2=4 (fit two batches)

Sandblasting Logic

The same worker is responsible for inserting the supports, loading and unloading the machine. The way he does that is to unload the bottles from the machine immediately after they are processed, and to load new bottles every time the machine is empty. While he waits for the process to be finished, he inserts supports to the bottles in stock, and loads and unloads the drilling machine. The activities priority regarding the worker assignment is, in a decreasing way, as follows: Unloading, Loading, Inserting Supports.

Making the worker wait until there's a batch to start filling the machine:

Every time a support is inserted, the bottle goes to a different queue depending on its type. For each queue, there's a dummy activity which collects the number of bottles of each type that the sandblaster can fit (9 or 12) and only then, the bottles go to the "sandblasting loading queue". This forces the worker to only start loading when there are the required number of bottles to fill the machine. Also, it prevents the loading activity to get stuck, because bottles will always be in order and batched correctly.

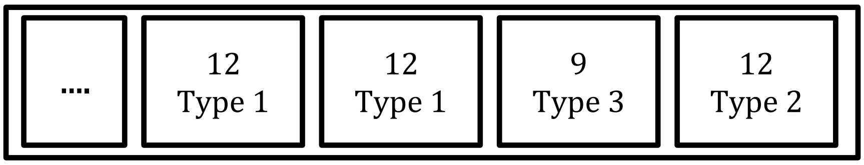


Figure 5.11- Sandblasting queue

Painting Logic

Bottles get painted while getting through an automatic conveyor which has capacity for 84 bottles. This is simulated in the software by creating a "queue" with a minimum waiting time equal to the time needed for a bottle to pass through the conveyor. The capacity is handled with the respective function in SIMUL8.

Removing the oxygen Logic

As told in the assumptions, every time bottles are removed from the "Removing the Oxygen area" to the "Acetonage machines", they are replaced with new ones, pulled from the stock. No worker involved.

Workers Allocation Logic

The way workers are allocated in the different activities is by making a daily check on the stock levels from the different areas in the factory and decide where they are needed the most.

For that purpose, there are two large groups of activities (that require workers) being considered. The first, in red, is composed by Control, Mixing, Filling, Top-Filling, and Furnace-Supply. The second one, in blue, by Finishing (Sandblasting, Drilling, Inspection, Acrochage), Acetonage (Loading/Unloading Acetonage and Gravage), Drilling, Cleaning and Auxiliary ones **[Figure 5.12].**

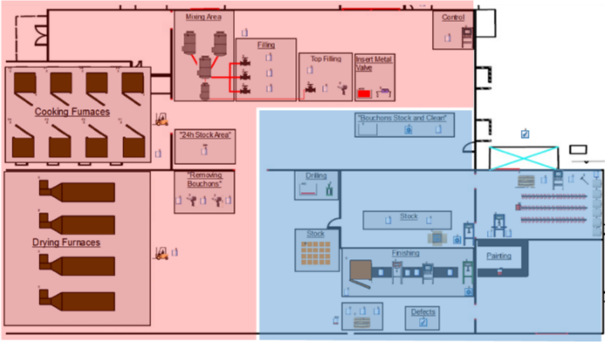


Figure 5.12 - Representation of two major groups of activities

The logic (which is schematized in **Figure 5.13**) starts with the **First Group** (in red). At the beginning of the day, the system checks if there are any bottles to be controlled, and if so it will assign a worker to that station. This information is taken from an already filled spreadsheet and it depends on the client's orders. "Filling" and "Top-Filling" work kind of the same way. If there is work to be done before the station, the system will assign the needed workers. (Example: if in a particular day, there are bottles to be filled, there will be workers allocated in that activity, otherwise there won't). A worker is also allocated to the "Mixing" activity every day that Filling is needed. The "Furnace-Supply" gets two workers assigned when a certain amount of batches (the needed to fill one "Drying Furnace") are ready from the "Cooking Furnace".

After everything is handled from the first group, the system starts to take care of the **Second Group**. Here, it will check how many workers are available (after the First Group Allocation) and decides where to assign them accordingly, as shown on **Table 5.1.**

Table 5.1- Decision table of how workers from the 2nd group are allocated

		Workers Available after the 1st Group Allocation							
		6	**5**		**4**		**3**	**2**	**1**
Number of workers to allocate in each activity	**Finishing**	4	4		4				
	Acetonage	2		2		2	2	2	
	Drilling		1	1		1	1		1
	Cleaning			1		1			
	Aux.			1					

When there are 4 or 5 workers available, the system can decide between Acetone or Finishing, depending on the stock levels before "Acetonage". If the stock is lower than 200 bottles, it will assign workers to "Finishing", otherwise they go to Acetonage.

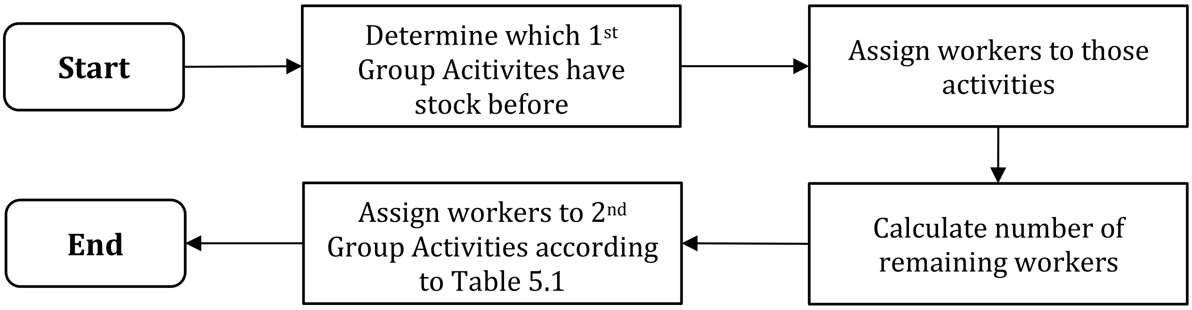


Figure 5.13 - Workers Allocation Logic

5.7. Results

Before proposing improvements and thinking about technological shifts, the current system needs to be studied first. This chapter will present the results gathered from the simulation model developed during the project, which were validated by the company.

The main input of the simulation model is an adapted version of the schedule relative to the Control Activity, in 2016. It regulates how many bottles entered the system over that period. Every simulation result both from the current model and the hypothetical scenarios will be based on it.

It's important to say that, due to the large number of industrial processes of this unit, just the main ones will be addressed. Sub processes like "painting the top" or "inserting stickers" will not be shown below, despite being present in the simulation model.

Parameters:

- Run Time: 322 days (explained below)
- Number of Runs: 5
- Warm-up Time: 0 (having information about the initial stock and being the production schedule different every day, there's no need to use this parameter since the system is balanced on day 0)

Initial stock:

- Stock of dried bottles: 50 pallets;
- Stock of painted bottles: 200 bottles;
- Stock of bottles having oxygen removed: 40*3=120 bottles.

Schedule information [Figure 5.14]:

- 1st January to 31st December;
- Summer Break between 1st August (Monday) to 3rd September (Sunday);
- Christmas Break between 24th and 31st of December.

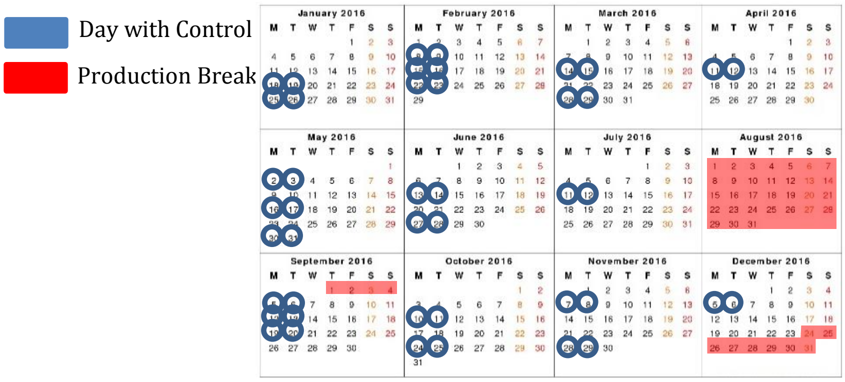


Figure 5.14 - Production Calendar

This means that from the 365 days of the year, only 322 belong to production period. After getting the weekends removed from the equation there are 232 days left when work can actually be done to fulfill the clients' orders **[Figure 5.15]**.

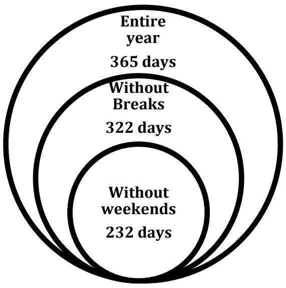


Figure 5.15- Working days

It's assumed that each day has 6,5 hours of continuous labour work, without breaks. Theoretically speaking it would be the same than the 8 hours with the breaks in between, so for simulation purposes there is no difference and it makes the system simpler.

5.7.1. Outputs

General outputs

- Number of bottles completed: 39.882 (higher than the number of bottles controlled because of the already existing stock)
- Number of defects after drilling: 2.173
- Average time in system: 21,5 days
- Average time being processed: 7,1days
- Average time being transported: 6 minutes
- Average time being handled (load/unload/etc): 2 minutes
- Average time waiting: 14,4 days

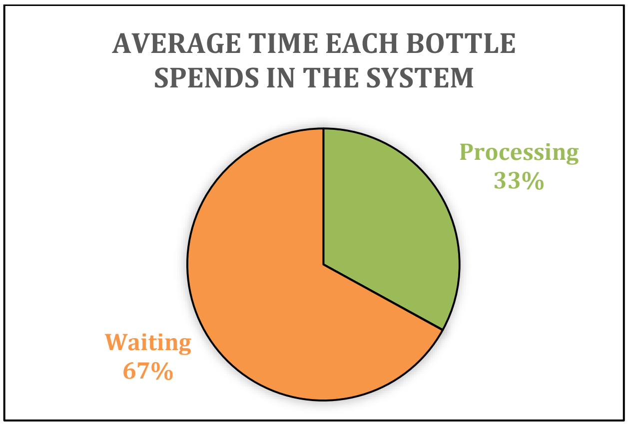


Figure 5.16- Distribution of the time each bottle spends in the system

Specific Activities' Output

For each specific activity, the analysis is made using these parameters:

-Waiting time→ Time the machine/activity is available and not working.
-Finished earlier → Time between the end of the day and the last time the activity processed a bottle/batch.
-Working time→ It's the time that the machine/activity is actually processing some bottle/batch.
-Blocked time→ Period of time the machine/activity has it's job done, but can't acept other bottle because either the next activity can't accept the current work item or the stock limit is reached.
-Resource starved time → The machine/activity is ready to start processing but the resource (worker) required is finishing other task.

All results **[Figure 5.17]** were adjusted so that they would only represent the days that each the activity is supposed to work (appart from the Furnaces, because otherwise they would appear to have 100% occupation rates).

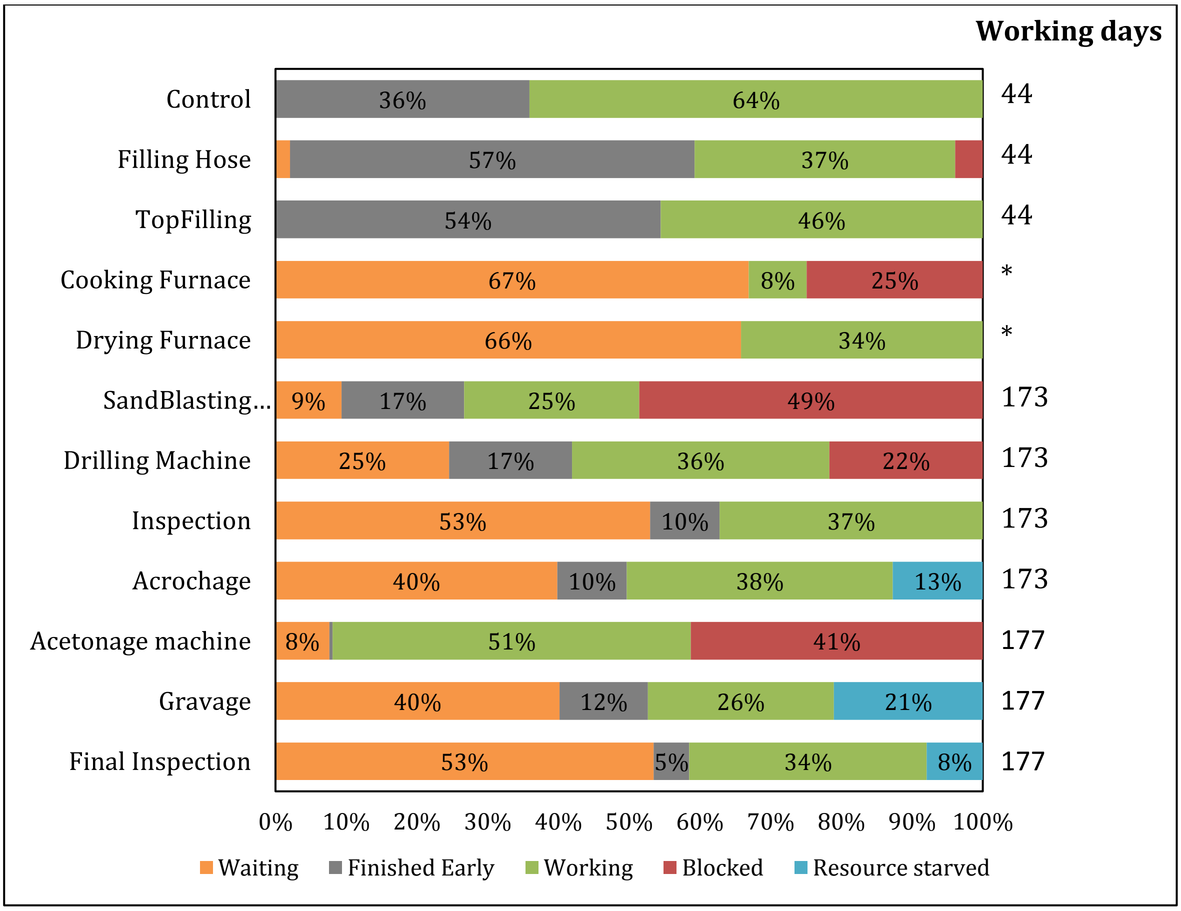


Figure 5.17 - Results gathered from the simulation regarding the specific activities/machines

It can be observed that there is a big percentage of time corresponding to the period when the workers finish their tasks before the end of the shift. At a first sight it might seem there's a problem with the simulation, but the fact is that due to the effort required to perform some of the tasks (by manually lifting large amounts of heavy material), the scheduling of the tasks is made so that workers don't need to continue working after completing all the work scheduled for that day.

The big percentage of Blocked Time in the SandBlasting Machine can be explained with the maximum stock of 24 bottles between this activity and the next one (Drilling). The worker responsible for unloading the machine, has to wait until there are only 12 bottles there to start unloading **[Figure 5.18]**.

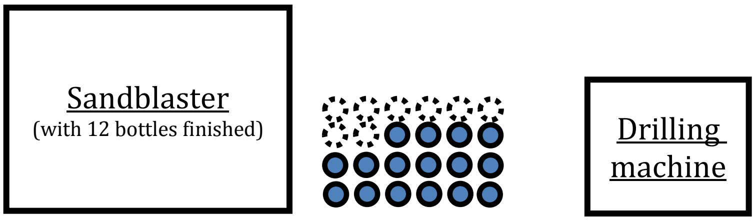


Figure 5.18- Example of "Blocked%"

Regarding the also big percentage of Blocked Time in the Acetonage Machines, it can be explained with the fact that bottles can have their Acetonage process finished, while the worker responsible for unloading them is still performing the next activity (Gravage).

Distribution of worker's Output

The charts presented below on **Figure 5.19** represent the distribution of the time that multi-tasked workers spend on the different activities.

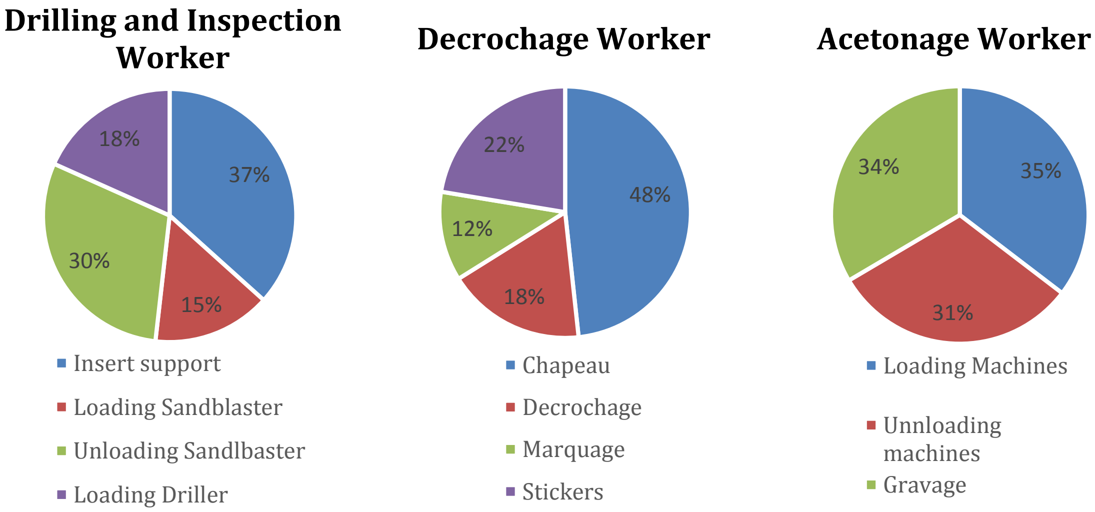


Figure 5.19- Distribution of worker's time

6. WORKER ALLOCATION CONCERNING MANUAL LIFTING

6.1. Theoretical Background on weight lifting

Studies have shown that workers who perform activities that require handling heavy materials by hand, are three times more likely to get back-pain related pathologies than the remaining ones. Despite not being fatal, these pathologies can be difficult to heal and cause great human and economic costs, since the ability to perform a certain task within the required time and quality decreases (Saavedra-robinson et al., 2012).

David (2005) gathers a wide range of methods that have been described in literature over the years, used to evaluate the exposure to ergonomic risk factors related to musculoskeletal disorders. Apart from vibration exposure (which doesn't apply to this particular case study), a method called NIOSH is the one that takes into account the larger number of factors, reason why was considered to be the most suited to deal with, in the Air Liquide's Industrial Process.

NIOSH is an equation developed in 1981 (which was later revised in 1991) by the American's National Institution of Operational Safety and Health, to assist on the evaluation of lifting demands, which is still used by safety and health practioners over the world (WATERS et al., 1993). It allows to calculate a lifting index (LI), providing relative estimates about how physically stressful a certain manual lifting task is. It depends on the following variables **[Figure 6.1]**:

H = Horizontal location of the object relative to the body
V = Vertical location of the object relative to the floor
D = Distance the object is moved vertically
A = Asymmetry angle or twisting requirement
F = Frequency and duration of lifting activity
C = Coupling or quality of the workers grip on the object

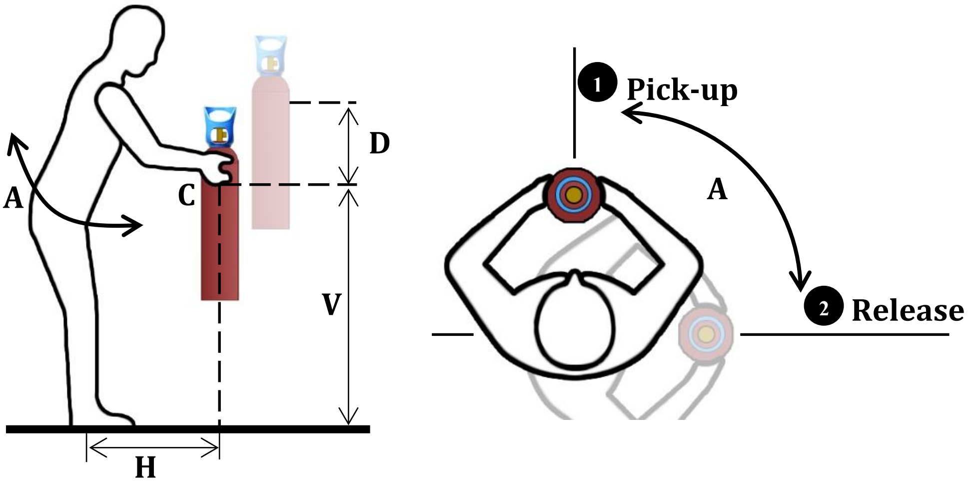


Figure 6.1 - Representation of NIOSH variables when lifting bottles

$$\boldsymbol{LI} = \frac{Load\ Weight}{Recomended\ Weight\ Limit} = \frac{L}{RWL} \qquad \textbf{(6.1)}$$

Where,

$$\boldsymbol{L} = weight\ of\ the\ lifted\ object \qquad \textbf{(6.2)}$$

$$\boldsymbol{RWL} = LC * HM * VM * DM * AM * FM * CM \qquad \textbf{(6.3)}$$

$$\boldsymbol{LC} = load\ constant\ of\ 23kg \qquad \textbf{(6.4)}$$

$$\boldsymbol{HM} = 25/H \qquad \textbf{(6.5)}$$

$$\boldsymbol{VM} = 1 - (0.003|V - 75|) \qquad \textbf{(6.6)}$$

$$\boldsymbol{DM} = 0.82 + 4.5/D \qquad \textbf{(6.7)}$$

$$\boldsymbol{AM} = 1 - (0.0032A) \qquad \textbf{(6.8)}$$

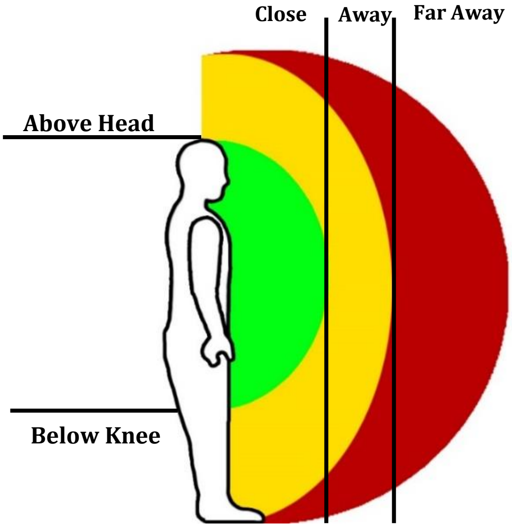


Figure 6.2 – Representation of the dangerous lifting positions

The Frequency Multiplier (FM) can be obtained from **Table 6.1** where values are grouped by work duration, number of lifts per minute and the vertical location (V).

Table 6.1 - Frequency Multiplier (adapted from WATERS et al., 1993)

Frequency Lift/min	Work Duration					
	≤ 1 Hour		>1Hour and ≤2Hour		>2Hour and ≤8Hour	
	V<75cm	V≥75cm	V<75cm	V≥75cm	V<75cm	V≥75cm
≤0.2	1	1	0.95	0.95	0.85	0.85
0.5	0.97	0.97	0.92	0.92	0.81	0.81
1	0.94	0.94	0.88	0.88	0.75	0.75
2	0.91	0.91	0.84	0.84	0.65	0.65
3	0.88	0.88	0.79	0.79	0.55	0.55
4	0.84	0.84	0.72	0.72	0.45	0.45
5	0.8	0.8	0.6	0.6	0.35	0.35
6	0.75	0.75	0.50	0.50	0.27	0.27
7	0.7	0.7	0.42	0.42	0.22	0.22
8	0.6	0.6	0.35	0.35	0.18	0.18
9	0.52	0.52	0.26	0.26	0	0.15
10	0.45	0.45	0	0.23	0	0.13
11	0.51	0.51	0	0.21	0	0
12	0.37	0.37	0	0	0	0
13	0	0.34	0	0	0	0
14	0	0.31	0	0	0	0
15	0	0.28	0	0	0	0
>15	0	0	0	0	0	0

6.2. Case study and current situation

As stated before in this document, this industrial process requires a lot of manual lifting which can lead to multiple injuries, back-pain related pathologies among others. The specific 7 activities that require weight lifting from the respective workers are presented below:

- Acrochage
- Acetonage
- Filling (Loading and Unloading)
- Sandblasting
- Control After Drilling
- Decrochage
- Final Inspection

Currently, the allocation of workers does not follow a scientific method regarding the balancing of manual lifting among workers. This leads to significant differences between the efforts required from the different workers. In the **Figure 6.3** we have the record of the total amount of weights lifted by each worker during 2016. Information about the kind of activities each worker did was not collected, so the analysis will be based only on the actual lifted weight.

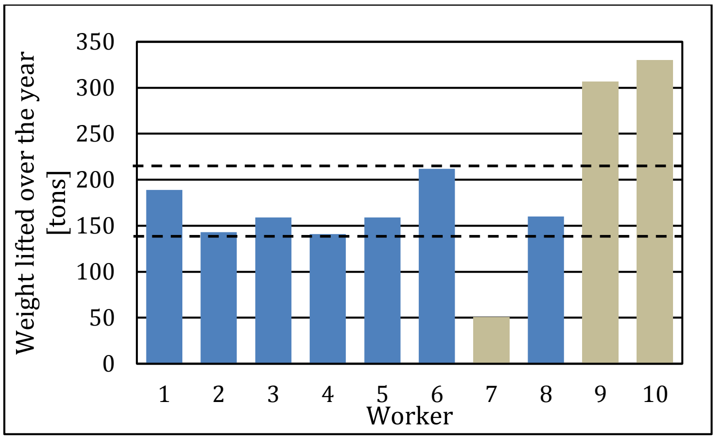


Figure 6.3 - Historical data from weight lifting in 2016

Even not considering worker 7, 9 and 10 (which was seasonal labor), the discrepancy is evident. The difference between the maximum and the minimum is 71 tons, and there's a standard deviation of 24 tons. It means that, in average, the most required worker lifted more 300kg per day than the least required one, being more exposed to health risks.

A proper assigment of these workers would minimize those overall risks. We are facing then, an allocation problem. While in the literature it's possible to find some allocation studies of similar problems, in the context of manual labor environment, like Tan et al. (2009) and Carnahan et al. (2010), none have been found on the daily assigment of human resources regarding weight lifting.

6.3. Objectives

Having the current production system in mind, algorithms were developed to balance the differences between the weights each worker is carrying. Minimizing this discrepancies, in addition to reducing overall health risks, creates a sense of fairness that can have a good impact on the employees' motivation levels.

Another purpose of this allocation is to smooth the successive weights each worker lifts over different days. This means that, in a 5 day period, it's different to lift 20kg every day, than to lift 100kg on one day and 0kg on the remaining 4 days.

What we are dealing with then, is a multi-objective optimization problem. This means that we are trying to improve simultaneously both parameters:

- Standard Deviation of the total weights each worker lifted over a period.
- Average of the Standard Deviations of the daily lifted weights for the different workers (individually).

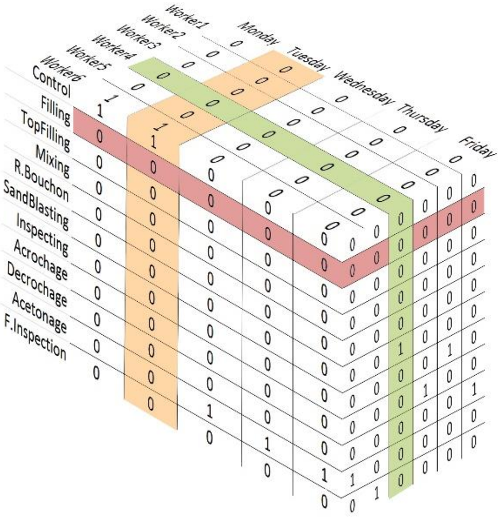


Figure 6.4 - Allocation output

Because of the lack of data, NIOSH equation parameters were not inserted in this study, so the only thing considered in the approaches below was the weight. However, the principles would be the same, and it would be just about changing the input.

Inputs:

The required outputs from the simulation to solve this problem are:

- Schedule= 2D binary matrix with information about what tasks were done each day [number_days]x[number_wstations]
- Weights= 2D matrix with information about the weight required to lift, in each task, each day [number_days]x[number_worktations]

Another important input required, provided by the company, are the worker restrictions due to skill or health disorders:

- Skills= 2D binary matrix with restrictions concerning the different workers at the different activities [number_workers]x[number_wstations]

6.4. Approaches

6.4.1. Mathematical model

In theory, this allocation problem can be fully optimized recurring to its mathematical formulation. Using a solver like IBM CPLEX or a similar one would be a possibility. Although, due to the large number of restrictions and variables, it wouldn't be possible to get an optimal solution in a reasonable amount of time.

Below, there's a representation of both objective functions and the respective problem restrictions:

Min:

$$\sqrt{\frac{\sum_{k=1}^{nw}\left(\begin{array}{c}\left(\sum_{i=1}^{nd}\left(\sum_{j=1}^{nws} allocation[i][j][k] * weights[i][j]\right)\right) - \\ \left(\frac{\sum_{k'=1}^{nw}\left(\sum_{i=1}^{nd}\sum_{j=1}^{nws} allocation[i][j][k] * weights[i][j]\right)}{nw}\right)\end{array}\right)^2}{nw}} \qquad \textbf{(6.9)}$$

And

$$\frac{\sum_{k=1}^{nw}\sqrt{\frac{\sum_{i=1}^{nd}\left(\begin{array}{c}\sum_{j=1}^{nws}(allocation[i][j][k] * weights[i][j]) - \\ \left(\frac{\sum_{i'=1}^{nd}\left(\sum_{j=1}^{nws}(allocation[i][j][k] * weights[i][j])\right)}{nd}\right)\end{array}\right)^2}{nd}}}{nw} \qquad \textbf{(6.10)}$$

Subject to:

$$\sum_{j=1}^{nws} allocation[i][j][k] = 1 \ \forall \ i = 1..nd \ , k = 1..nw \qquad \textbf{(6.11)}$$

$$\sum_{k=1}^{nw} allocation[i][j][k] = schedule[i][j] \ \forall \ i = 1..nd \ , j = 1..nws \qquad \textbf{(6.12)}$$

$$allocation[i][j][k] \leq skills[k][j], i = 1..nd \ , j = 1..nws \ , k = 1..nw \qquad \textbf{(6.13)}$$

Given:

- **schedule:** 2D binary matrix with information about what tasks were done each day
- **weights:** 2D matrix with information about the weight required to lift, in each task, each
- **skills:** 2D binary matrix with restrictions concerning the different workers at the different activities
- **nd:** number of days;
- **nw:** number of workers;
- **nws:** number of working stations;

Having as Decision Variable:

- **allocation:** Desired output. 3D matrix represented by **Figure 6.4**;

Equations **(6.9)** and **(6.10)** are the objective functions we are trying to minimize. The first represents the standard deviation of the total amount of weight lifted over a period, between the different workers. The second, an average of the individual standard deviations of the daily lifted weights. Both functions should be combined in one, by attributing different weights like so (for example 0.5 for both):

$$Objective\ Function: F = \lambda_1 f_1 + \lambda_2 f_2, \tag{6.14}$$

$$where: \lambda_1 + \lambda_2 = 1 \tag{6.15}$$

Concerning the restrictions, equation **(6.11)** makes sure that each day, each worker is only assigned to one activity. Equation **(6.12)** ensures that, each day, workers are only assigned to activities that are supposed to work. The last restriction **(6.13)** keeps workers from performing activities when they are not apt (lack of skills or health conditions).

6.4.2. Constructive heuristic

One of the approaches to solve this problem was to build a constructive heuristic that would create a good solution from scratch. It works by allocating the 6 workers in the different tasks, every day, following this main premise: "If you lifted heavy today, you will lift lighter tomorrow".

Since some tasks have a lot less skilled workers than others, for each day, the allocation starts with those (the more exclusive ones), preventing skilled workers from being allocated to other tasks first (which would lead to unfeasible solutions). In case of a tie, the algorithm chooses the lighter one (because the point is to allocate here the most required worker yet).

Even so, some problems might occur. Let's picture this scenario, where, in this particular day, activities A-B-C-D-E-F are working:

Table 6.2 - Hypothetical cumulative weight

Worker	Cumulative weight lifted
1	600 Kg
2	500 Kg
3	400 Kg
4	300 Kg
5	200 Kg
6	100kg

Table 6.3 - Constructive algorithm steps

Activity	Skilled Workers	Weight Required	Iterations			
			1st	2nd	3rd	4th
A	1,2,3,4,5,6	4000				
B	2,3	5000			**3**	3
C	2,3	6000				**X**
D	1,2,3,4,5,6	3000				
E	4,5	1000	**4**	4	4	4
F	2,3,4	2000		**2**	2	2

As illustrated in **Table 6.3**, in the 4th iteration the algorithm would try to allocate a worker to Activity C. The problem is that the only skilled workers (2 and 3) were already allocated in other activities, in the previous iterations. To solve this problem, the algorithm goes to the previous allocated activity and try the next worker with more cumulative weight, consecutively.

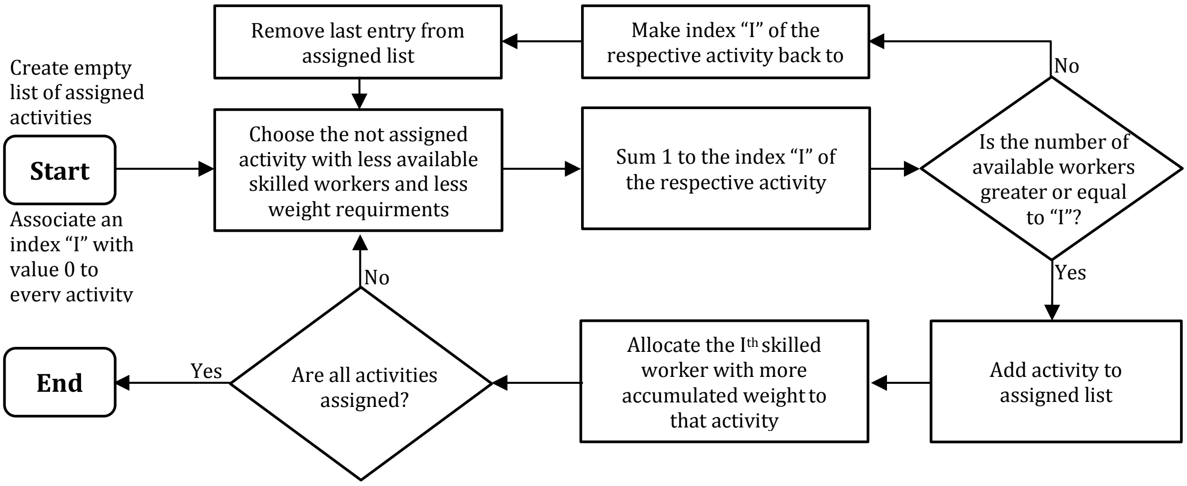


Figure 6.5 - Explanation of the Constructive Heuristic Algorithm

6.4.3. Metaheuristics

Since optimization is not possible in a reasonable amount of time and since constructive heuristics can usually lead to bad solutions (or at least far from optimal), another approach was taken in order to solve this problem in hands. Metaheuristics are commonly used in optimization problems like this, because they can reach very good solutions (if not optimal) in a considerably short amount of time. They are appropriated in real-world situations, when (Michalewicz & Fogel, 2004):

- The number of possible solutions is so large that an exhaustive search for the best answer would not be reasonable.
- The problem is so complex that in order to get any answer, we have to simplify the models of the problem so much that any result is useless.
- The evaluation function that describes the quality of solutions is noisy or varies with time, requiring not just a single solution but an entire series of solutions
- The possible solutions are so constrained that the simple construction of a feasible answer is difficult, let alone searching for the optimal one.
- The person solving the problem may be inadequately prepared or imagines some psychological barrier that prevents them from discovering a solution.

It can be said that the first and forth points referenced above are the main reasons why metaheuristics where thought as good alternatives to the methods studied before in the document. According to (Blum & Roli, 2003) they can be classified into two main groups:

- **Trajectory methods** – The term comes from the fact that these methods are characterized by a trajectory in the search space. Common examples are: Tabu Search, Simulated Annealing and Iterated Local Search.
- **Population-based methods** – These algorithms deal with a set of solutions in every iteration, rather than a single solution. Because of that, they provide a natural and intrinsic way of exploring the search space. Examples are: Evolutionary Algorithms and Ant Colony Optimization.

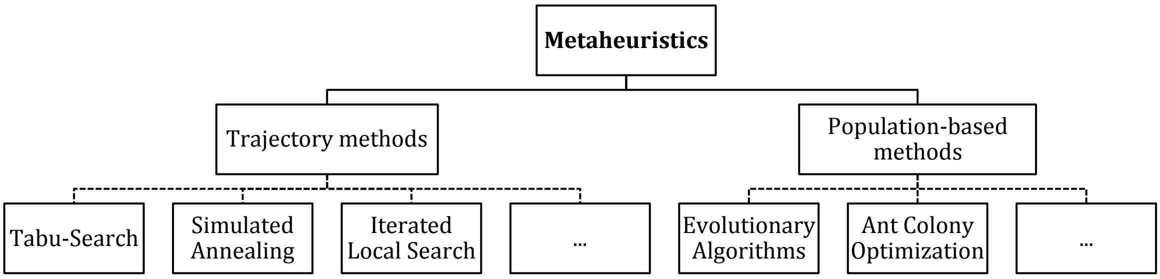


Figure 6.6 - Examples of metaheuristic algorithms

To study the allocation of workers regarding weight lifting, one specific type of Evolutionary Algorithm was chosen: The Genetic Algorithm. The reason for the choice has to do with the fact that these algorithms are particularly well-suited for dealing with multi-objective problems (Konak et al., 2006).

6.4.3.1. List Algorithm

Klement et al. (2017) proposed an hybridization of a metaheuristic and a list algorithm on the resolution of resource assignment problems **[Figure 6.7]**. The List algorithm would assign different tasks to the available resources based on their order on a certain List (considering the problem constraints), building a feasible solution. Then, some objective function would evaluate that solution, which, according to that evaluation, could be accepted or not by the metaheuristic.

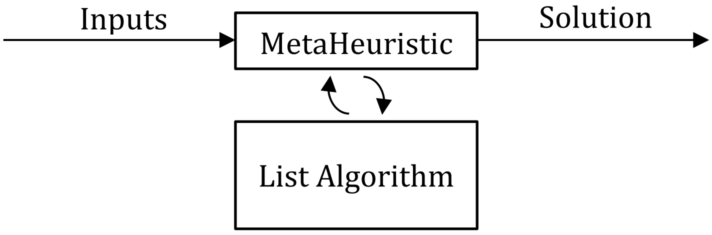
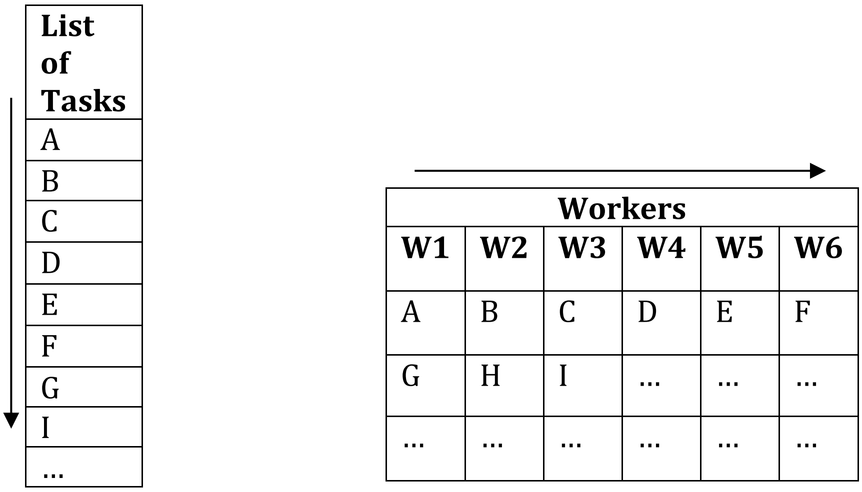


Figure 6.7 - Hybradization methaeuristic (Adapted from Klement et al. (2017))

Lists Algorithms are usually used to distribute a list of tasks in a set of available resources over time. A standard approach to this algorithms is to assign each task, by order, into the first available machine (Zhu & Wilhelm, 2006), in this case, the first available worker. Having the example of **Figure 6.8**, if no restrictions are applied, tasks can be allocated by order from the first worker to the last, like so:



List of Tasks
A
B
C
D
E
F
G
I
...

Workers					
W1	**W2**	**W3**	**W4**	**W5**	**W6**
A	B	C	D	E	F
G	H	I	...	...	...
...	...	...	...	...	...

Figure 6.8 - List Algorithm Principle

Replacing the list of tasks by pairs "(day, activity)" can make this algorithm generate solutions for the problem in hands. Instead of A,B,C,D,E,F,G,H,I, it would be 1A, 1B, 1C, 1D, 1E, 1F, 2B, 2C, etc (in the case where activities A to F worked on the first two days). The problem is that allocating from left to right doesn't take into account the restrictions. As mentioned before, some workers can only do some tasks.

To solve this, a small binary matrix is created for each day with the following dimensions: workers and working activities. This matrixes allow to create, for each day, a preferable order of workers to allocate. First, we calculate, for each activity, how many workers are able to work on it **[Table 6.4]**. Then, for each worker, we determine how many activities he can do that can only be made by one worker, by two workers, and so on **[Table 6.5]**. The aim is to see what workers can do the most exclusive tasks. Those will get their activities assigned, preferably, on last.

Table 6.4 – Restriction Matrix

Restriction Matrix				
	A	**B**	**C**	**D**
W1	1	0	0	1
W2	1	1	1	0
W3	1	0	1	0
W4	0	0	1	0
Sum	**3**	**1**	**3**	**1**

Table 6.5 - Decision Matrix

	Decision Matrix			
	1	**2**	**3**	**4**
W1	1	0	1	0
W2	1	0	2	0
W3	0	0	2	0
W4	0	0	1	0

Order of preference: W4, W3, W1, W2
Logic: Order workers by column 1,2,3 and 4 in the decision matrix **[Table 6.5]**

Supposing the list of Tasks is A, B, C, D: Task A can be done by workers 1,2,3. Following the order of preference, we assign this task to W3. Task B can be done only by worker 2 so we assign it to the respective worker. Task C can be done by worker 2,3,4. Following the order of preference we assign it to W4. Task D is assigned to the remaining worker, W1.

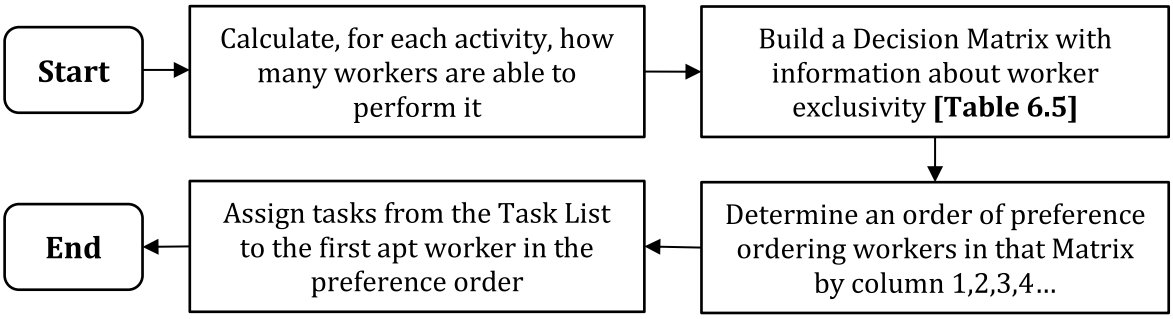


Figure 6.9 - Explanation of List Algorithm

6.4.3.2. Genetic algorithm

This metaheuristic is inspired in the evolutionist theory of natural selection and its basic principles were first proposed by Holland (1975). The concept is that within a population, strong individuals have a greater opportunity to transmit their genes to future generations via reproduction, whereas the weak and unfit are faced with extinction. Random mutations can also occur. If they bring additional advantages to the individual, they are kept, otherwise they are naturally eliminated (Konak et al., 2006).

As stated in **Section 6.4.3**, Genetic Algorithms are population-based metaheuristics. This means that they handle multiple solutions in each iteration, instead of just one. Those sets of solutions are called populations, whereas solutions themselves are called *chromosomes* **[Figure 6.10]**, made by discrete units called *genes*.

For the problem in hands, these *chromosomes* represent ordered lists of tasks (like **Figure 6.8**), being the different *genes* the pairs "(day, activity)".

1B	10C	4F	5D	10A	30G	12C	5A	...	29E

Figure 6.10- Example of a chromosome

In the pursuit for improvement, Genetic Algorithms use two important operators to build new solutions from already existing ones: *crossover* and *mutations*. The first consists on combining two *parent chromosomes,* creating one or more *offspring chromosomes* with information coming from both. The second one, as the name suggests, creates an anomaly in one or more genes of the *chromosome*.

Between each iteration, selection is applied, keeping the size of the population unchanged and choosing only the strongest solutions (according to some objective function) to survive into the next generation.

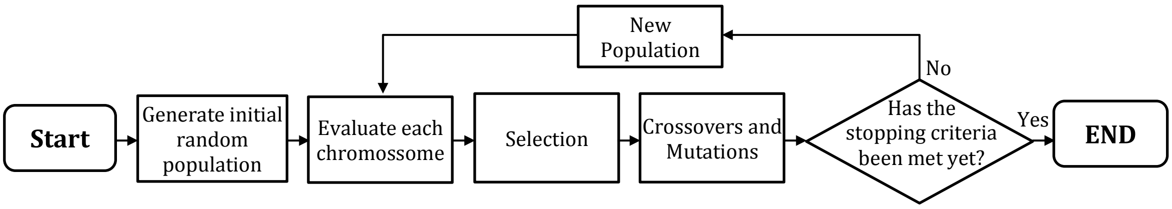


Figure 6.11 - Standard Genetic Algortihm Approach

Before implementing, some parameters have to be defined first: the size of the population, the mutation and crossover rate, and the stopping criteria. For the last, the most common are: limit on the number of generations, limit on the number of evaluations, limit on the chance of achieving significant changes in the next generations (limit on the number of generations without improvement) (Safe et al., 2004). Because of its simplicity, the first was the one used in this document.

Crossover

While the meaning of this operator was already explained above, there are multiple ways to perform crossovers. (Otman & Jaafar, 2011) gathers some of the most known methods described in literature:

- Uniform Crossover Operator;
- Cycle Crossover (CX);
- Partially-Mapped Crossover (PMX);
- Uniform Partially-Mapped Crossover (UPMX);
- Non-Wrapping Ordered Crossover (NWOX);
- Ordered Crossover (OX);

Due to the nature of the *chromossomes*, the “Ordered Crossover (OX)” was the one used in this particular problem. It allows to perform this operation without the risk of having repeated genes (which would lead to unfeasible solutions) **[Figure 6.12]**.

The way it works is by choosing two random *chromossomes* from the current generation (the parents) and two random numbers (representing two positions). The corresponding substring from the first parent is inserted in the offspring. Then, the non-repeated elements from the second parent are inserted by order in the blank chromosomes. To generate the second crossover, the same method is applied starting with the second parent.

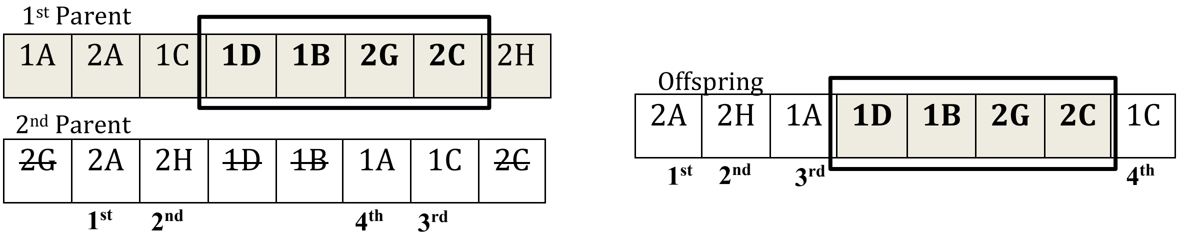


Figure 6.12 – Ordered Crossover (OX)

Mutation

In order to introduce some randomness and to further avoid getting stuck in local optima, Genetic Algorithms use this operator replicating the natural phenomena of mutations. The way it works is by swapping two random chromosomes from a random solution picked in the current population as shown on **Figure 6.13**.

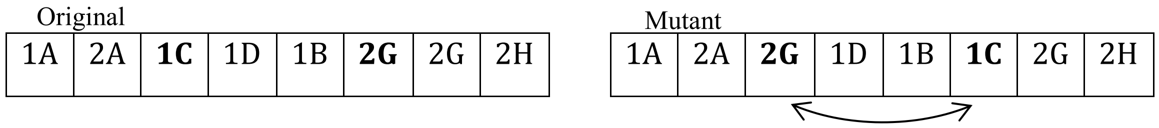


Figure 6.13 - Mutation

6.4.3.3. Multi-objective approach

In this case-study a multi-objective problem is being considered, which means that a standard GA approach would not work. There is a need to continuously improve both objective functions, which do not necessarily decrease with each other.

Several approaches on using Genetic Algorithms with Multiple Objective Problems have been documented in literature. Konak (2006) collects the most common ones, with a detailed description of each.

For this particular problem, the chosen technique is called NSGA-II, a well-tested method which has been proved to be efficient in these kind of problems.

NSGA-II

The way this method evaluates solutions is to order them by non-dominated fronts **[Figure 6.14]** and, then, inside each front, by crowding distance **[Figure 6.15]**. This is because, for every population, solutions that belong to a certain ith front have never worst values of both objective functions, than solutions in some (i+n)th front. Regarding the crowding distance algorithm, it is used to find, in each front, how far away from neighbors each solution is. That way, the spread of solutions is preserved (Deb et all, 2002).

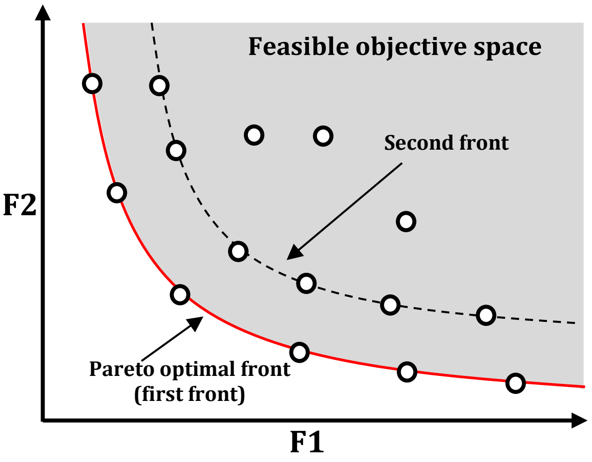


Figure 6.14 - Non dominated fronts sort

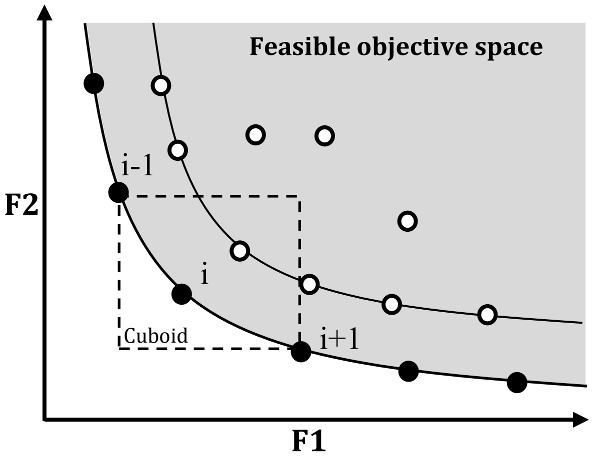


Figure 6.15 - Crowding distance sort

Fast Nondominated sorting approach:
Each solution is compared with all others in terms of Pareto domination. The ones that cannot be dominated by any other solution, belong to the first front (Pareto's optimal front). To find the remaining fronts, the same logic is followed, without considering solutions belonging the already found fronts. (Ozkis & Babalik, 2017).

Crowding distance approach:
This methodology allows us to calculate the density of the location of solutions in the population (Ozkis & Babalik, 2017). It's about finding the distance between each solution and its closest neighbors.

For each objective function, the end solutions (with the smallest and largest value) are assigned an infinite distance value. All the others are assigned a distance equal to the difference in the function values of two adjacent solutions (Deb et al., 2002).

Overall implementation:

The way the whole algorithm was implemented will be shown below **[Figure 6.16]**:

- Generate a population with size N_{pop}.
- For each iteration (generation):
    - Create N_{cross}% random crossovers. Each crossover results in two different descendent solutions.
    - Randomly choose N_{mut}% from which a mutation is applied.
    - All corresponding solutions (both initial and descendent) are obtained using the list algorithm, and sorted by non-dominated fronts and crowding distance
    - Select the first N_{pop} solutions to be the new population.

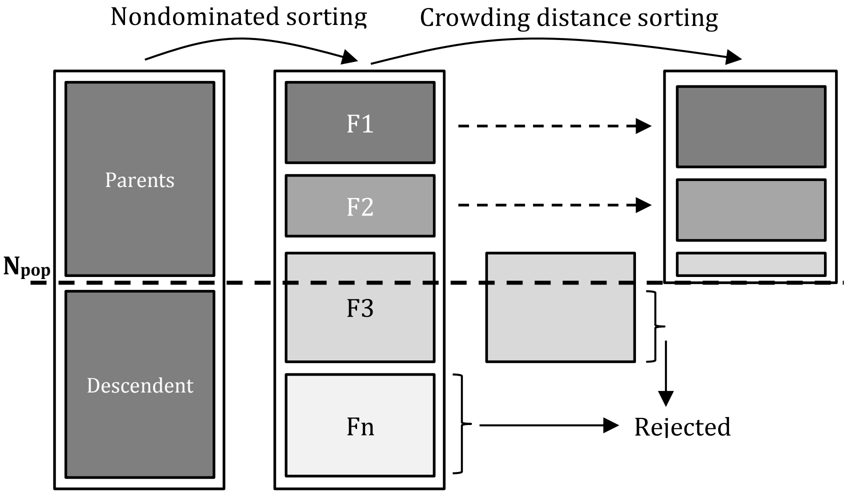


Figure 6.16 - Overall Implementation

6.5. Results

Constructive Heuristic

The results obtained from this constructive heuristic, based on the 2016 schedule, show that this method can improve significativly the discrepances between the weight carried by the diferent workers **[Figure 6.17]**.

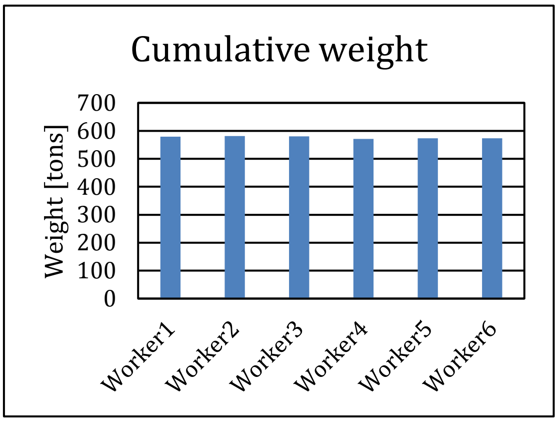


Figure 6.18 - Weight distribution over workers

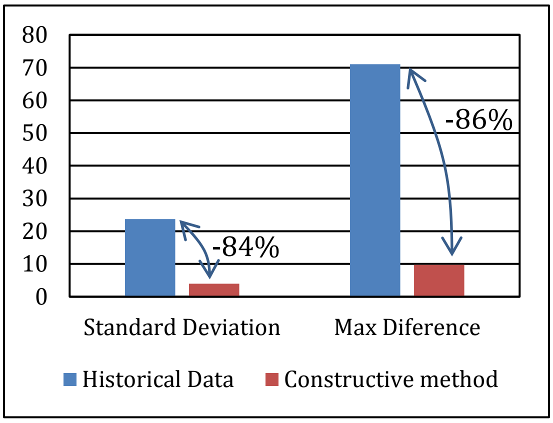


Figure 6.17 - Comparison between historical data and algorithm

Comparing to the historical data, there's a reduction on 84% in the standard deviation between different workers and a decrease of 86% on the maximum difference between the most required worker and least required one, which now comes to 9,8 tons.

Genetic Algorithm

To simplify the problem and reduce the computation time, only a one month period was considered when using the Genetic Algorithm. This period is still reasonable because either way, it would not be possible to precisely predict how production will go and which activities will run each day over the duration of an entire year (due, for example, to changes in the client's orders).

The following table **[Table 6.6]** presents the parameters used on the implementation of the algorithm. These values were reached after successive experiments above which solutions tended to stabilize.

Table 6.6 - Genetic Algorithm Parameters

GA parameters	Value
Number of generations	500
N_{pop}	100
N_{cross}	50%
N_{mut}	10%

Figure 6.19 shows the first front solutions of all generations, since the first population until the last. One advantage of this method is that the decision-maker can choose, after all calculations are done, what solutions fits him better. For example, in this case, they can choose the solution that optimizes the first objective function, the second objective function, or some that satisfies both.

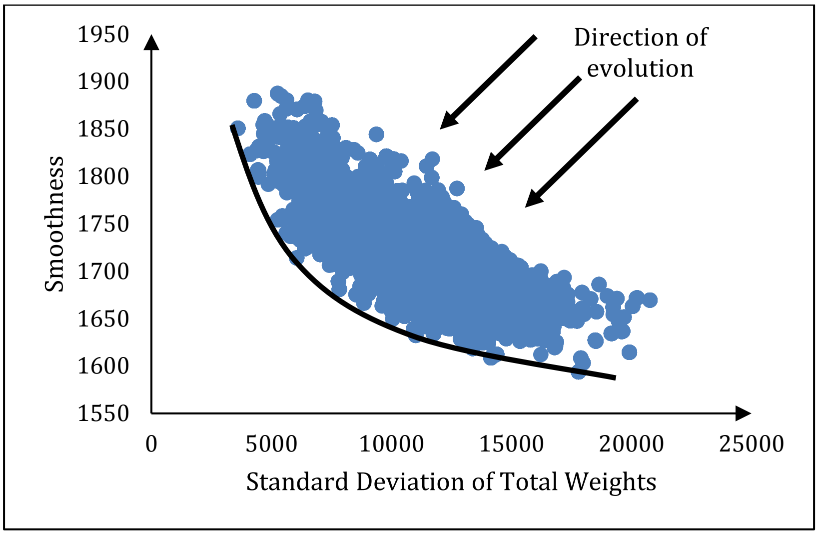


Figure 6.19 - First Front Solutions of every generation

For example, the solution that optimizes the standard deviation of the total weights (the one more to the left) has a value in that objective function of 1851kg , which comparing to the one obtained by the constructive heuristic (2104kg) is 12% lower **[Figure 6.20]**.

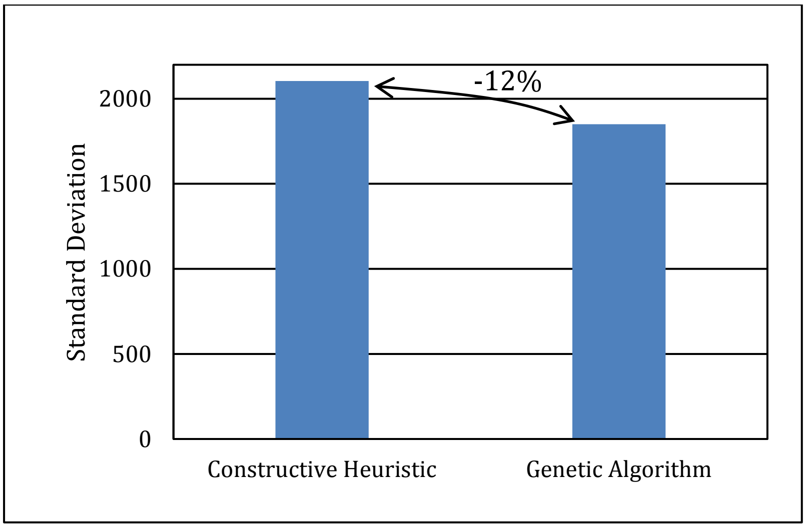


Figure 6.20 - Standard deviation results on the two methods

7. SCENARIO THINKING

In this chapter, different scenarios will be studied to understand what are the possible changes that most likely would benefit the industrial unit. The number of bottles completed over the year, the average stock before finishing tasks, the average time in system, and the maximum weight lifted per worker, were the chosen KPI to compare different scenarios.

First, Tuning Simulation Scenarios were carried out, which considered keeping the exact same layout, number of workers needed in each activity, and working flow. A sensibility analysis was made on the production volume, and then, on a company's request, a study about the introduction of one more worker in the industrial site. Then, more complex scenarios were studied, which implied, in some cases, the automation of processes with the objective of releasing workers to other tasks.

7.1. Tuning Simulation Scenarios

7.1.1. Production volume (6 workers)

Increasing the production volume means increasing the number of empty bottles that enter the system. By keeping the usage of drying furnaces to 1 and all other assumptions referenced above **[section 5.5]**, the only option is to try filling the furnace in the weeks it is not currently working. Although, there is a limit above which more bottles IN do not translate into more bottles OUT. As an example, filling the furnace every week would not be a feasible solution because of the limited number of workers which would not be enough to perform the finishing tasks. **Table 7.1** shows the point when that capacity limit is reached, corresponding to a number of bottles controlled 40% higher.

Table 7.1 - Sensibility Analysis on the production volume

Bottles IN	Number completed	Average stock before finishing [pallets]	Average time in system [days]	Maximum Weight lifted per worker (using constructive heuristic) [kg]
Current Situation	39.807	7,6	22	581.126
More 10%	42.356	11,4	24	669.194
More 20%	44.944	13,3	25	717.145
More 30%	47.593	15,4	26	766.479
More 40%	49.222	42,3	42	795.675
More 50%	47.925	80,5	63	----------

7.1.2. Production volume (7 workers)

Since the company already fulfils all the orders with the current workers, adding one worker would not bring immediate evident benefits. It can eventually smooth production and change its capacity, which will be studied below **[Table 7.2].**

Table 7.2 - Sensibility Analysis on the production volume with one more worker

Bottles IN	Number completed	Average stock before finishing [pallets]	Average time in system [days]	Maximum Weight lifted per worker (using constructive heuristic) [kg]
Current Situation	39.807	6,7	21	568.613
More 10%	42.357	8,7	22	586.332
More 20%	45.011	9,8	23	627.417
More 30%	47.675	10,7	23	670.119
More 40%	50.150	22,2	29	743.080
More 50%	52.700	50,9	44	788.961
More 60%	50.910	60,2	48	----------

As it was expected, increasing the number of workers, while keeping the exact same workflow, increases the capacity of the industrial site to produce more units per year **[Figure 7.1]**. Also, keeping the production volume, there would be a decrease of 12,5 tons on how much the most required worker had to lift over the entire year.

Figure 7.1 – Bottles IN vs Bottles OUT

7.2. Technological shifts Simulation Scenarios

This section will describe the benefits and/or drawbacks of possible technological approaches. Detailed technical specifications about how those technologies would work will not be discussed in this document. They were selected based on company suggestions, on the desire to decrease weight lifting, or because of identified bottlenecks.

7.2.1. Mixing Activity [Scenario 1]

Currently, the mixing task **[Section 2.2]** is done semi-automatically, with the help of one worker, who needs to feed the machines with the raw material. This keeps the worker busy all day, not allowing him to help with other tasks. The problem is that the containers

don't have enough space to store the necessary amount of porous mix needed for that day, which means that the worker has to remain there during a full daily shift.
The suggestion here is to either create an automatic feeding system or to increase the volume of the containers (adding more or replace them by bigger ones). The effect, in both cases, is the same, which would be to release one worker to do other tasks.

7.2.2. Automate the Bouchon Treatment [Scenario 2]

As described before, the Bouchon is a cover for the bottles that needs to be inserted before going to the cooking furnace, and removed and cleaned after that period. All related activities do not add any value to the final product and therefore are a waste of human resources.

Having a very geometrical form, it would be relatively easy to automate their transportation, drilling and cleaning **[Figure 7.2]**, releasing workers from those activities.

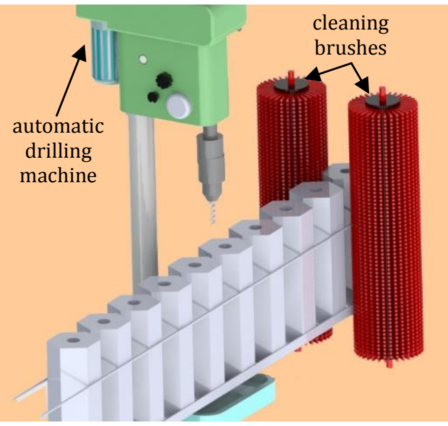


Figure 7.2 - Simplistic and Illustrative approach to the given suggestion

7.2.3. Reducing one worker in Filling Activity [Scenario 3,4]

The filling activity can be described as semi-automatic. While the bottle is being filled, there's no need for human intervention, but the loading and unloading are done manually, requiring two workers. The suggestion here is to use the same technique used in the TopFilling. The bottles remain in the floor (no need to load/unload) and a worker uses one or more hoses to fill them **[Figure 7.3]**. This would release one worker from this activity.[Scenario 3].

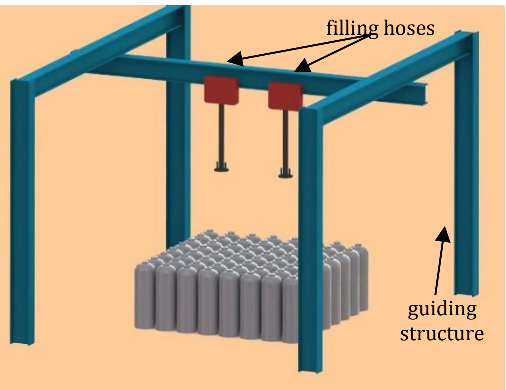


Figure 7.3 - Illustrative representation of the Filling suggestion

A possibility, which could be discussed with the mechanical engineering team, would be to fully automatize the axis on this structure, removing completely the necessity of a human resource [Scenario 4]. Both suggestions will be studied in the simulation and in both there will be the assumption that the processing times would be the same.

7.2.4. Free Acrochage worker [Scenario 5]

The painting activity doesn't require a dedicated worker since the process itself is automatic. Although, loading and unloading the conveyor is still done manually, with a worker at each station respectively. Since the worker who does the unloading also needs to perform other activities such as inserting a sticker and Marquage, automatizing the loading **[Figure 7.4]** before the unloading would be a good start. The other tasks currently performed by the Acrochage worker could be done by the inspection worker since that activity has a big Waiting%.

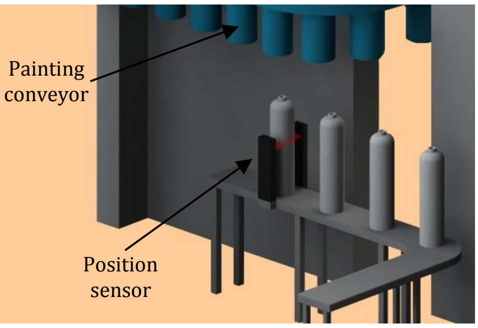


Figure 7.4 – Illustrative representation of a possible automatic acrochage station

7.2.5. Automatize reading bottle's number [Scenario 6]

Currently, a dedicated worker is responsible for inspecting the bottles and manually typing the respective ID in a computer. That's a very time consuming activity, monotonous, repetitive and sensitive to human error. This scenario studies the impact of inserting an automatic reading system **[Figure 7.5]** that could eliminate the need of manual typing.

For simulation purposes it was assumed that it would take in average 10 seconds to see any defects in the bottle and scan the respective serial number. Since this particular activity has a high percentage of waiting time, there's not much expectations about immediate improvements in the material flow.

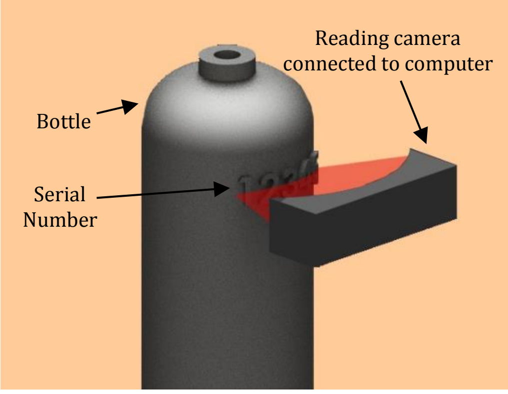


Figure 7.5 – Illustrative representation of an Hypothetical Serial Number

7.2.6. Two Drilling Machines [Scenario 7]

As seen on the VSM, the drilling machine is the bottleneck of the finishing group. This scenario will study the effect of introducing another drilling machine (with the same cycle time), which could work on parallel with the existing one **[Figure 7.6]**.

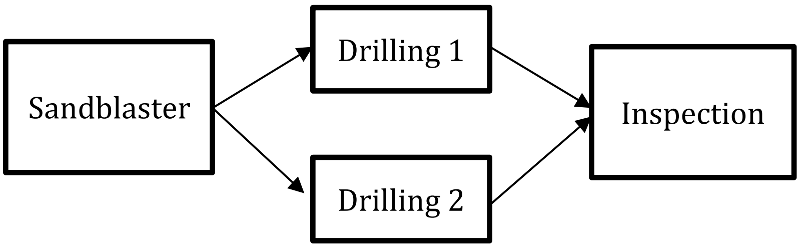


Figure 7.6 - Paralell Drilling

7.2.7. Results

The results relative to the scenarios presented above are shown in **Table 7.3**. In the following page **[Figure 7.7]**, a combination of scenarios is analyzed.

Table 7.3 - Comparison between the different proposed scenarios

	Average stock before finishing [pallets]		Average time in system [days]		Maximum Weight lifted per worker (using constructive heuristic) [kg]	
Current Situation	7,6	-----	22,1	-----	581.126	-----
Scenario 1	7,4	⇩	21,7	⇩	623.391	⇧
Scenario 2	7,6	⊜	22,1	⊜	581.126	⊜
Scenario 3	7,4	⇩	21,7	⇩	554.475	⇩
Scenario 4	6,8	⇩	21,3	⇩	553.969	⇩
Scenario 5	6,7	⇩	21,5	⇩	525.591	⇩
Scenario 6	7,6	⊜	22,1	⊜	581.126	⊜
Scenario 7	6,0	⇩	21,9	⇩	581.126	⊜

Scenario 2 would not bring any immediate improvement since the "Bouchon Treatment" is only done when some particular worker is not needed somewhere else. Although, it could have some impact on the overall motivation levels since the related tasks are very repetitive and monotonous. Regarding the investment, it shouldn't be large due to the operation's simplicity.

All other scenarios (apart from the 6th) have a good impact in the overall process. Scenario 6 doesn't translate in any change because Inspection is located before the already identified bottleneck of the finishing line, the Drilling station. Any change in the Inspection would not lead to an overall improvement of the process. Although, as it happened in Scenario 2, this change would make the worker's life a lot easier. In this case, because they wouldn't have to type manually the bottle's ID, which is a very time consuming activity, and, as mentioned before, sensitive to human error.

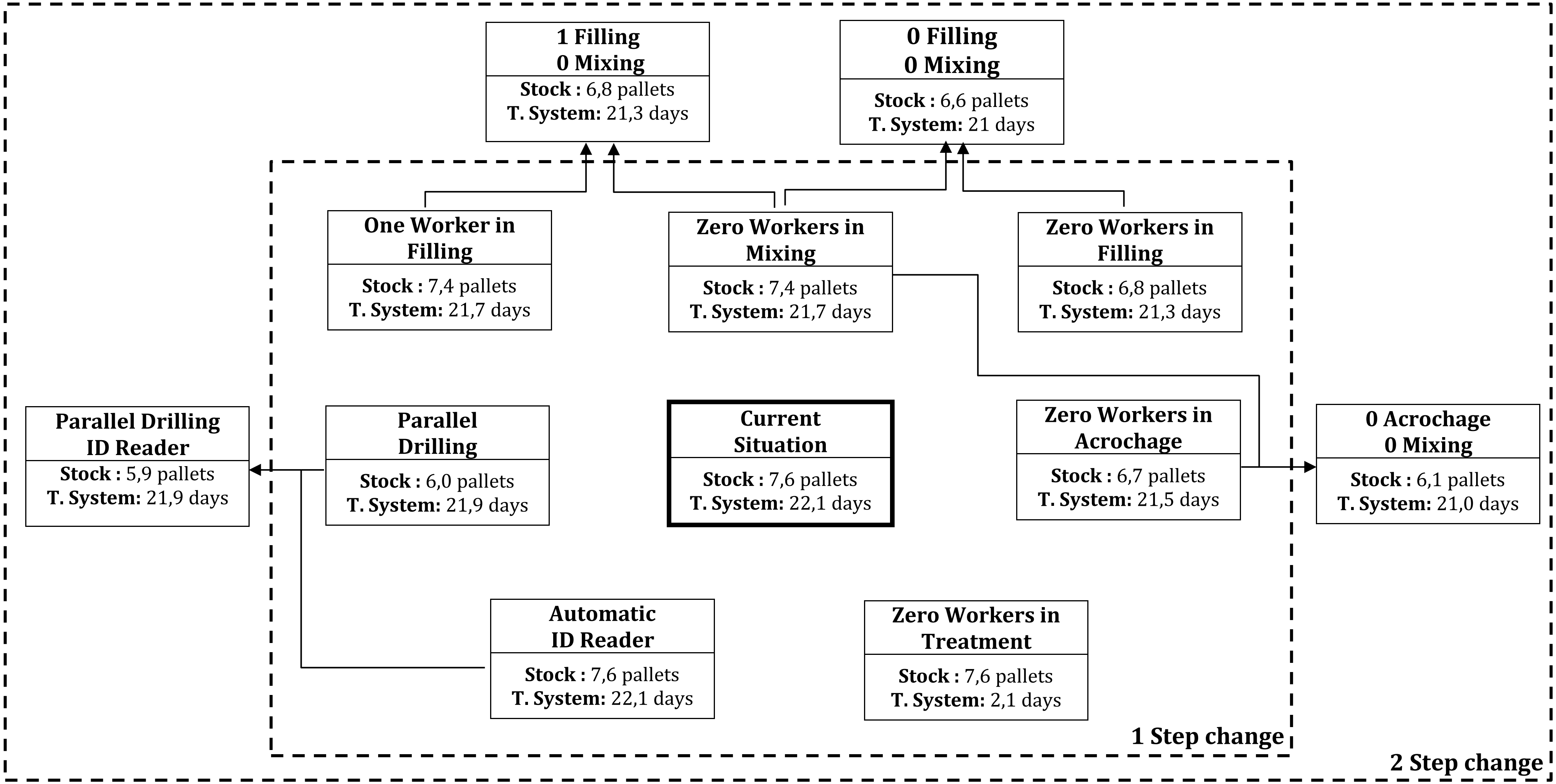


Figure 7.7 - Combined scenarios

8. LAYOUT

8.1. Theoretical Background

Jiang & Nee (2013), refers to the Facility Layout Planning (FLP) as being the design of allocations plans of the machines/equipment in a manufacturing shop floor. Usually addressed during the factory's design stage (prior to construction), it can be often subject to studies and evaluations as the business and manufacturing system naturally evolves over the years.

The importance of this matter can be easily justified by the impact it has on the overall operational costs. According to (Tompkins, 2003) 15-70% of the operational costs are related to the layout, and improving these layouts can reduce them at least by 10-30%.

(Raman et al., 2009) proposed as effectiveness factors to evaluate layouts, the productive area utilization, the closeness gap (which includes the travel distances and material handling), and the layout's flexibility. Due to recent pressures on the reduction of greenhouse effect and energy consumptions, (Amar & Abouabdellah, 2016) proposed the increment of those key performance factors, as described in **Figure 8.1**.

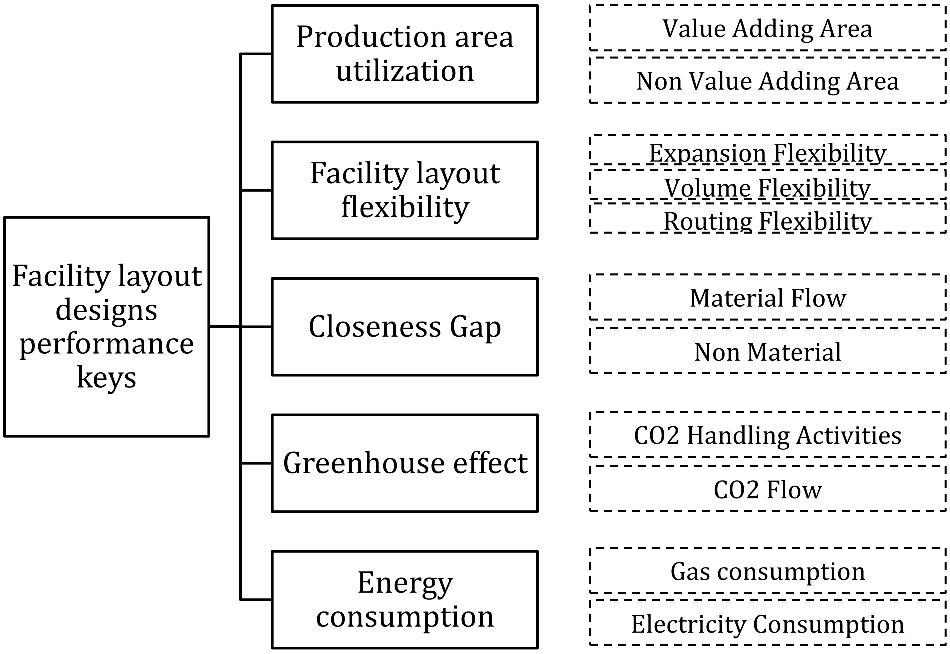


Figure 8.1 - Key performance for FLP (adapted from Amar & Abouabdellah, 2016)

Two widely applied approaches to design and plan the layout of some facility are Algorithmic and Virtual Reality (Jiang & Nee, 2013). While the Algorithmic ones focus on the formulation of the problem (using different models) and then solving them using metaheuristics such as GA our Simulated Annealing, the Virtual Reality is an alternative that allows the users to manually plan the design using their experience and knowledge acquired over the years (by using simple drafts or recurring to CAD/3D Softwares). Simulation is also a powerful tool to analyze different layout scenarios, regardless of how they were obtained (Shannon, 1998).

8.2. Case study application

The Facilities Layout is one of the aspects that Air Liquide wants to improve. The current routes force the product to go back and forth and they even have some crossing points. With data gathered from the company it was possible to determine that, each bottle travels in average 170 meters from the moment it enters the system until it's ready to leave the facility. In **Figure 8.2** it is possible to see how bottles currently move inside the unit during the production process.

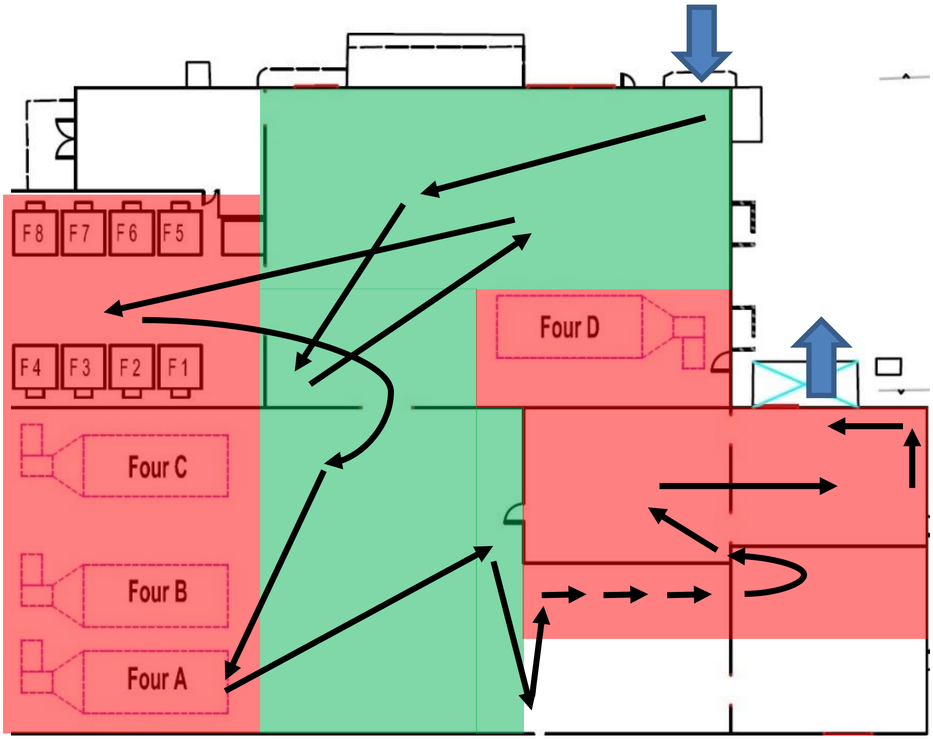


Figure 8.2 - Current Layout Flows

In red are the areas less likely to suffer a change in layout. Having into account the buildings characteristics and size of the equipment's, both drying and cooking furnaces are the hardest equipment to move inside the unit. The finishing (from sandblasting to shipping) are already quite optimized concerning the product's route and the exit point, so its layout will not be studied either.

Regarding the evaluation parameters gathered from the literature, shown in **Figure 8.1**, only the distance between successive departments will be addressed (included in closeness gap). The flexibility is not that important in this particular industrial unit, since their products all face the same trajectory, regardless of their size. For the Greenhouse and Energy Consumption there is not available data, but nonetheless they should have a direct relation with the distance that bottles go through.

8.3. Proposals

Trying different positions for each workstation can virtually lead to an infinite number of possibilities. Although, since this industrial process can be described as a pure flowshop (meaning that every product always go through the same workstations by the same order) the process of finding a good solution becomes easier. That is why there was no need to use algorithmic methods. After some iterations with the company, it was possible to select 3 good proposals that can decrease significantly the distance between different activities.

The first proposed solution **[Figure 8.3]** was thought keeping the industrial process exactly as it is. Following the process order, the Filling station would become closer to Control, and then, the Top Filling station, closer to the Cooking Furnaces. The 24h stock area would be in the middle. This way, the flow of material wouldn't have crossing points and the products wouldn't have to go back and forth.

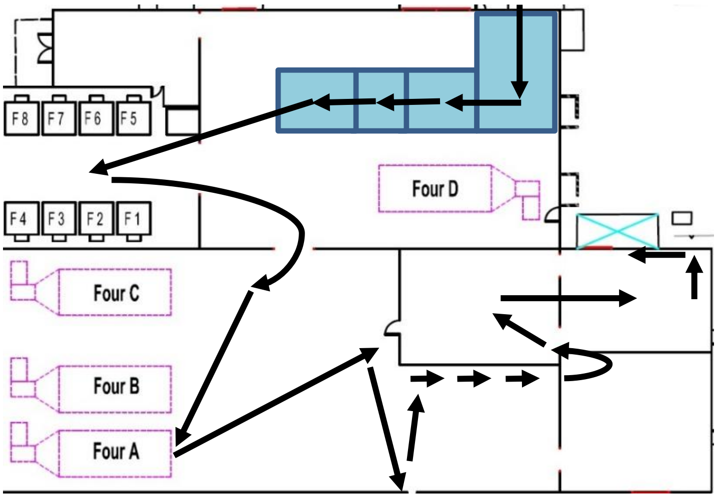


Figure 8.3 - Layout Proposal "order by precedencies"

The second one **[Figure 8.4]**, not so evident, consists on having two parallel stations that can both perform Filling and TopFilling. Doing so would remove the necessity of a stock area since the bottles would remain overnight in the respective station. This way, each station would perform, alternately Filling and TopFilling in successive days.

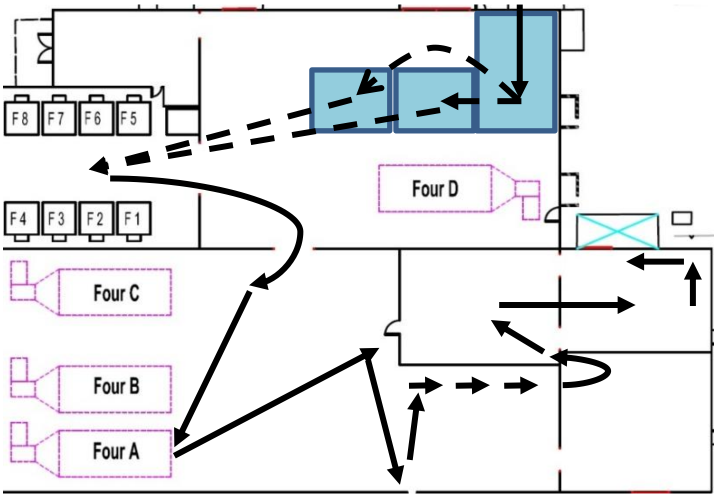


Figure 8.4 - Layout Proposal "Alternate Filling"

The last one **[Figure 8.5]**, takes advantage of the fact that only one Drying Furnace is needed. Since in any situation, the “24h Stock Area” would no longer be in the place it currently is, that zone could be used to remove the bouchons and then the bottles would go directly to the Drying Furnace D, instead of going to Furnace A. As can be seen in the Figures, there’s a significant difference in terms of distance and flow organization.

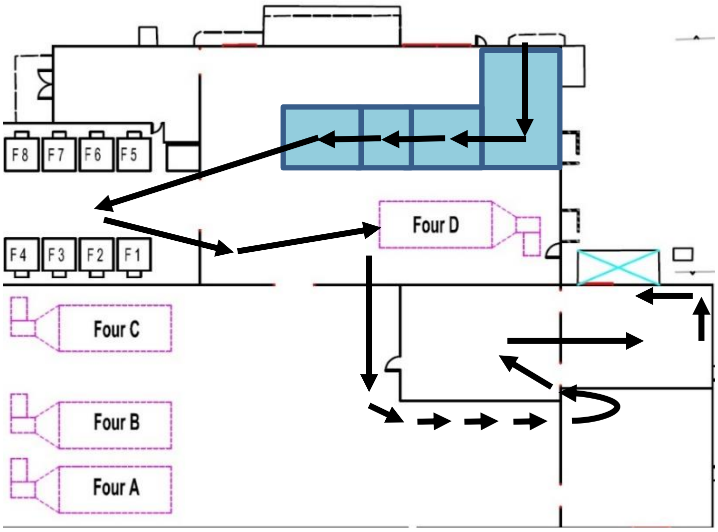


Figure 8.5 - Layout Proposal "Use Fournace D"

8.4. Results

As mentioned before, in this particular industrial unit, the fact that all long transportations either represent periods of time much shorter than the processing activities, or are done outside working hours, makes it difficult to evaluate the impact of different layout proposals. The only possible way to quantify their difference (apart from parameters such as overall organization or cleanness of the routes, which were already discussed) is to compare the distances that bottles go through **[Figure 8.6]**.

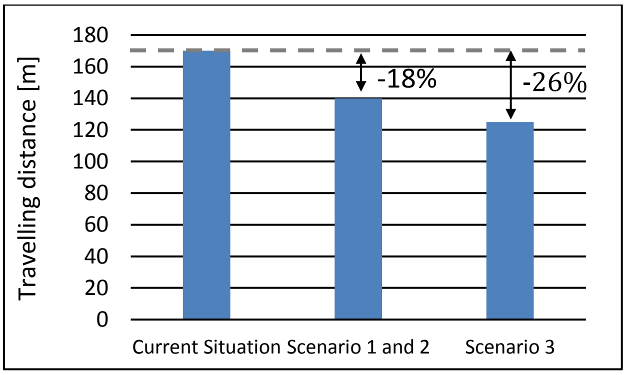


Figure 8.6 - Comparison between the distances each bottle go through in the different scenarios

Both scenarios 1 and 2 represent a decrease in the traveling distance of 18% when comparing to the current situation. Scenario 3, by making use of a different furnace, represents a decrease of 26%. These are results that can have great impact on the production process in the future, even if they don’t directly affect it at the moment.

9. CONCLUSIONS

This document gathered all the consulting work and results obtained during the externship on Air Liquide. From the simulation model, to the workers' allocation, scenario thinking and layout proposals, it is safe to say that all these particular studies gave interesting results and met the initial objectives.

Simulation was proved to be a very powerful tool: both to provide greater knowledge about the process and its activities, but also to give valuable data regarding hypothetical scenarios of change. This will allow the company to make better informed decisions before jumping into any investments.

The distribution of weight lifting between the different workers took also an important role on this study. Without any kind of technological shift, keeping the exact same workflow, and spending no money, this report showed that it is possible to smooth the weight lifting effects and decrease the differences between workers up to 85%, recurring to different heuristics.

At last, layout proposals were made in order to decrease the total distance traveled by a bottle from the beginning of the process until the end. One of them, results in a decrease of 25% of that value when comparing to the current situation. This can have a great impact in the future (when technological shifts occur), even if it does not right now.

Summing up, this Report shows the importance of studying the product flow inside an industrial unit before thinking about technological shifts. Most changes in industrial processes require considerable investments and should not be analyzed individually, since the outcome will depend on the global interaction of all activities.

9.1. Future Work

Only the processing times relative to one type of bottle have been considered. In the future, the remaining ones will be produced and it will be possible to collect the respective processing times. Therefore, the simulation model can be further detailed, being able to give more accurate results, closer to the real world.

Regarding the lifting distribution, in the future, heuristics can take into account other factors besides the weight (NIOSH formula). A simple software with graphic interface can be created, having as input the future schedule of the working activities and giving as an output a good solution for the workers' allocation.

The Layout routes can also be further analyzed in the dimensions of Green House Effect and Energy Consumption.

Gaps were identified in the literature concerning the allocation of human resources in different workstations according to ergonomic factors such as weight lifting. This means that there is room to show the methodology and results before the scientific community.

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APPENDIX A

Appendix A – Processing Times

Activity		Average time to complete
Control		18 sec/bottle
Filling	Loading	10 sec/bottle
	Machine	30 sec/bottle
	Unloading	10 sec/bottle
	Transport each batch to Stock Area	66 sec/pallet
Top-Filling	Transport each batch from Stock Area	???
	Top-Filling	12.8 sec/bottle
	Insert bouchon	Masked time
	Clean clothes	Between 2-3 minutes/batch
	Clean pallet	Between 3-4 minutes/batch
	Transport to cooking Furnace (1st 2batches)	3min/batch
	Transport to cooking Furnace (2nd 2batches)	2.5min/batch
	Transport a new pallet to top filling	???
Cooking Furnace	Cooking Furnace	48h
Cooking To Drying	Remove each 2 batches to stock	76.4 sec/2batches
	Transport each batch to Remove the bouchon area	76.7 sec/batch
	Remove each metal valve	6.2 sec/bottle
	Remove each Bouchon	3.2 sec/bottle
	Transport batches to drying	???
Drying Furnace		5days
Transport batches from drying to stock		after work (will not consider any worker here, time=0)
Transport each batch from stock to sandblasting (when needed)		???
Sandblasting	Inserting support	8sec /bottle
	Loading each bottle	4.2 sec/bottle
	Open Door+Time in machine+Closedoor	14s+3.5m+14s
	Unload each bottle	8.2 sec/bottle
Drilling	Loading	3-5 sec/bottle
	Drilling	35 sec/bottle
	Unloading (the sandblast worker)	3-5 sec/bottle
Inspection		35.7 sec/bottle
Painting the top		2.7 sec/bottle
Inserting the robinet		5.5 sec/bottle
Screw the robinet		26 sec/bottle
Acrochage		6.5 sec/bottle
Painting		1h
Marquage		2.6 sec/bottle
Stickers		5 sec/bottle
Decrochage		4 sec/bottle
Chapeau		10.9 sec/bottle
Transport to stock		3 sec/bottle
Transport from stock to "Remove the Oxygen"		???
"Remove the Oxygen"		1h
Acetonage	Loading	32.7 sec/bottle
	Machine	5.2 min
	Unloading	21.8 sec/bottle
Gravage		72 sec/bottle
Final Inspection		34.9 sec/bottle

APPENDIX B

Appendix B.1 – Confidence Intervals Tuning Scenario (6 workers)

Bottles IN	Number of bottles Completed			Average Stock Before Finishing [pallets]			Average time in system [days]		
	Min.	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**
Current Situation	39678	39807	39936	7,5	7,6	7,8	21,9	22,1	22,2
More 10%	42211	42356	42500	10,4	11,4	12,3	23,9	24,5	25,1
More 20%	44865	44944	45020	12,1	13,3	14,4	24,5	25,3	26,1
More 30%	47491	47593	47692	14,5	15,4	16,3	25,7	26,2	26,7
More 40%	48835	49222	49608	39,4	42,3	45,1	40,1	41,8	43,5
More 50%	47490	47925	48359	77,4	80,5	83,6	60,5	62,3	64,1

Appendix B.2 – Confidence Intervals Tuning Scenario (7 workers)

Bottles IN	Number of bottles Completed			Average Stock Before Finishing [pallets]			Average time in system [days]		
	Min.	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**
Current Situation	39690	39805	39920	6,5	6,7	6,8	21,0	21,2	21,4
More 10%	42246	42357	42468	8,3	8,7	8,9	22,1	22,3	22,5
More 20%	44946	45011	45075	9,5	9,8	10,1	22,4	22,6	22,8
More 30%	47586	47675	47764	10,5	10,7	11,0	22,7	22,9	23
More 40%	49758	50150	50542	21,6	22,2	22,7	29,0	29,2	29,4
More 50%	52500	52700	52953	50,3	50,9	51,7	43,7	44,1	44,4
More 60%	50500	50910	51235	59,7	60,2	50,4	47,6	48	48,2

Appendix B.3 – Confidence Intervals Technological Scenarios

	Average Stock Before Finishing [pallets]			**Average time in system [days]**		
	Min.	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**
Current Situation	7,5	7,6	7,8	21,9	22,1	22,2
Scenario 1	7,0	7,4	7,7	21,6	21,7	21,8
Scenario 3	7,0	7,4	7,7	21,6	21,7	21,8
Scenario 4	6,6	6,8	6,9	21,2	21,3	21,4
Scenario 5	6,5	6,7	6,8	21,3	21,5	21,7
Scenario 6	7,5	7,6	7,8	21,9	22,1	22,2
Scenario 7	5,8	6,0	6,2	21,8	21,9	22,1

Appendix B.4 – Confidence Intervals Technological Scenarios (Combined)

	Average Stock Before Finishing [pallets]			**Average time in system [days]**		
	Min.	**Avg.**	**Max.**	**Min.**	**Avg.**	**Max.**
Scenario 1 and 3	6,6	6,8	6,9	21,2	21,3	21,4
Scenario 1 and 5	5,9	6,1	6,3	20,8	21,0	21,1
Scenario 1 and 4	6,4	6,6	6,8	20,	21,0	21,1
Scenario 6 and 7	5,8	5,9	6,2	21,8	21,9	22,0