Variability causes in the manufacturing and assembly of complex products

Daniela Sofia Pedro da Silva

Master dissertation

Tutor at FEUP: Prof. Américo Azevedo

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

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The greatest teacher, failure is.

Master Yoda

Abstract

Industrial companies, especially the ones operating on the technological field, face high competitivity and a constant evolution of the market. While a controlled production process leads to good performance and satisfied customers, continuous improvement is essential to keep growing and gain competitive advantage in the market. When supplying companies in the food and pharmaceutical industries, that also operate under extreme competitivity, delivering products on time is crucial; therefore, knowing production lead-times is vital to meet deadlines.

Knowing customer demand and being able to make forecasts is of great help for a good performance, as well as a good and under control production process. Variability plays a crucial role in both cases: high demand variability means unworthy forecasts and process variability hampers quality and a good performance.

This study was conducted as part of a continuous improvement plan of a company that manufactures industrial equipment, framed in a strategy of growth. The main goal was to quantify the variability existent in the production process and identify its root causes, aiming to define an improvement plan for reducing variability and keep the process under control.

An analysis of the production process was made, studying the processes and the flow between them, measuring production times and quantifying waste. Besides a high variability of demand, the study also identified a process out of control and with high variability due to discrepancies between the information presented in the system and the reality, problems in materials flow and lack of tools and information. It was critical to address the root causes affecting not only variability, but also the value added to the process.

With the main problems and their causes identified, an improvement plan was designed to mitigate variability effects and improve the process. Long term actions, as implement standard work were included on the plan, with the perspective of continuous improvement.

The implementation of the defined plan highlighted a crucial factor on continuous improvement projects that is often forgotten: the need to properly manage change. Without a shift on cultural change and the full collaboration of everyone, this type of projects may accomplish some improvements at the beginning but fail in long term.

The inexistence of a sense of urgency, the disbelief in administration and in the possibility that things could change and the disagreements between mid-management provided a great obstacle to the improvements. It was not possible to implement the defined plan and observe its impact on the process, as almost everyone in production, despite referring that things needed to change, wasn't willing to truly do something.

To successfully implement a project of continuous improvement, change shall be properly addressed in advance by administration, making employees feel their contribution to the growth of the company.

Análise de variabilidade na produção e assemblagem de produtos complexos

Resumo

As indústrias, especialmente as que operam no ramo tecnológico, enfrentam uma grande competitividade e uma constante evolução do mercado. Enquanto processos sob controlo levam a uma melhor performance da empresa e mantêm os clientes satisfeitos, a melhoria contínua é essencial para o crescimento da empresa e para a vantagem competitiva da mesma. Para empresas que fornecem a industria do alimentar e farmacêutica, que também operam em mercados de grande competitividade, é necessário cumprir os prazos de entrega definidos, pelo que é essencial conhecer o *lead-time* correto dos produtos.

Conhecer a procura do consumidor e ser capaz de fazer previsões é bastante importante para uma boa performance, assim como um processo de produção sob controlo. A variabilidade desempenha um papel importante em ambos os casos: uma grande variabilidade da procura significa a impossibilidade de fazer previsões e a variabilidade do processo prejudica a qualidade e performance.

Este estudo foi realizado como parte de um projeto de melhoria contínua, inserido numa opção estratégica de crescimento. O principal objetivo foi quantificar a variabilidade existente no processo de produção e identificar as suas causas, para definir um plano de melhoria para reduzir a mesma e estabilizar o processo.

Foi feita uma análise do processo produtivo, examinando os processos e os fluxos entre os mesmos, medindo tempos de produção e quantificando o desperdício. Para além de uma elevada variabilidade da procura, este estudo também identificou processos fora de controlo, devido a discrepâncias entre as informações registadas no sistema e a realidade, problemas no fluxo de materiais e falta de informações e ferramentas adequadas. Tornou-se crítico definir as causas-raiz que afetam a variabilidade assim como o número de atividades de valor não acrescentado.

Com os problemas definidos e as suas causas identificadas, um plano de melhoria foi elaborado de forma a diminuir a variabilidade do processo. Ações a longo prazo, como a implementação de *standard work*, foram incluídas no plano, numa perspetiva de melhoria contínua.

A implementação do plano definido enfatizou um fator crucial em projetos de melhoria contínua que é frequentemente ignorado: a necessidade de gerir a mudança. Sem uma alteração da cultura e a colaboração de todos, este tipo de projetos pode atingir melhorias em fases iniciais, que normalmente não conseguem ser mantidas a longo prazo.

A inexistência de um sentido de urgência, a descrença na administração e na possibilidade de mudança e os conflitos entre a gestão intermédia afiguraram-se como grandes obstáculos. De facto, não foi possível implementar o plano definido e quantificar o seu impacto no processo, uma vez que, apesar de todos referirem que era necessário mudar as coisas, ninguém estava realmente disposto a fazê-lo.

Para uma implementação de um projeto de melhoria contínua bem-sucedida, a mudança deve ser abordada desde o início pela administração, levando os colaboradores a sentir a sua contribuição para o crescimento da empresa.

Acknowledgements

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To all, a big thank you.

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Acronyms

ATO Assemble to Order
BOM Bill of Materials
BVA Business-value added
CTQ Critical to Quality
CV Coefficient of Variation
ETO Engineering to Order
JIT Just-in-Time
LT Lead Time
LSS Lean Six Sigma
MTS Make to Stock
NVA Non-value added
PO Production Order
SW Standard Work
TQM Total Quality Management
VA Value-added
VOC Voice of the Customer
VSM Value Stream Map
WIP Work in Progress
WT Weighted Total

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1 Introduction

This work explores variability causes on the assembly of complex products and how they can be reduced, being the result of a project of process improvement on an industrial company, as part of the Industrial Engineering and Management's master thesis.

This chapter presents the definition of the problem in analysis, as well as a description of the proposed objectives and of the methodologies used to achieve them.

1.1 Context

Competitiveness is a key factor for companies' survival. As result, over the last decades, companies have strived to improve their performances through several approaches and focusing on different aspects of the processes.

If a company wants to stay at the same level as their competitors, it needs to operate with a high level of predictability, meaning that the processes are stable and under control. This way, meeting deadlines shall not be a problem, leading to satisfied customers and improved performance.

However, when the opposite happens, this is, when instead of predictability, the processes have high variability, performance usually decreases. As so, one of the major goals of every company is to reduce as much as possible the factors that create variability, taking advantage of all sorts of management tools to do so.

Despite the economic crisis in Portugal, the company in analysis has been growing, mainly due to its policy of continuous improvement. To act as a lead partner for multinational companies, high focus on costumers and commitment to meet deadlines are essential goals. As mentioned above, reducing process variability is essential to achieve this level of performance and allow the company to keep growing.

1.2 Problem and Objectives

The studies conducted in the scope of continuous improvement identified a problem that, without the appropriate treatment, can jeopardize the goal of meeting deadlines: a high variability on production lead time of complex products.

By complex products, one refers to products that must go through several different operations, requiring heavy machinery work, with a lot of parts to be assembled at the final stage. One cannot disregard this, since the more stages a process has, and the more parts incorporate the final product, the higher the variability is.

This, combined with the high variability on customer demand, creates the need of a well-defined production strategy.

Therefore, the present study, with the duration of about 4 months, is focused on variability analysis, with the aim of improving the company's performance through the improvement of production processes.

Although the main purpose was to reduce the variability of production times, it was considered that the best way to act was to look at the overall process (instead of looking to each stage individually) and identify causes of variability and non-value-added activities. As, quite often, non-value-added activities are linked to higher variability a study was conducted to answer the following questions:

- What are the main causes that lead to the high variability existent?
- How can these causes be eliminated or reduced?
- What is the current state of the process: how many activities exist that add no value to the process?
- How are these non-value-added activities affecting the process variability and how can they be eliminated?
- Do the movements done by workers on the shop floor contribute to the identified variability? If so, how can they be reduced?

Once these questions have been answered, a plan of actions can be defined and implemented to improve the processes and a methodology to approach similar problems in the future can be created.

1.3 Methodology

This project was developed accordingly to the chronogram provided by the company (Appendix A) and based on the DMAIC[1] structure. To start, two project charts were made and placed at the ongoing projects board to assure that the team knew what the project was about and which the deadlines were.

The first step was to realize an ABC/XYZ analysis to identify the most significant products in terms of production quantity and costs, as well as understand their demand patterns. This allowed choosing a small number of products to be tracked on the next phases: measure, analyse and improve.

The observation phase consisted, entirely, in field work. The assembly of some of the selected products was followed, through direct observation, to register production times and calculate the deviation from the time defined on the bill of materials (BOM) and identify possible causes of variability.

In parallel, all observations regarding movements between buildings and types of activities (value-added (VA), business-value-added (BVA) and non-value-added (NVA)) were registered, to assess the process state and understand the impact of these activities in production time variability.

The analyse phase firstly required the quantification of all the data collected, presenting it in a way that could easily be understood by other people (graphics, tables). An individual analysis of problems and their causes was also done.

After that, the results and the individual analysis were presented to a small team composed by elements in charge of the production department. Based on some proposed solutions, a brainstorm session was done to get to the root cause of the problems and delineate solutions to the major problems identified. The results were represented on an Ishikawa diagram and a plan of action was defined. As several improvements were selected, there was the need to understand in which order they would be done. All proposed improvements were classified according to their execution time, difficulty, cost, and impact. A weighted total (WT) of classification was calculated, and the sequence of improvement actions was defined: the action with the higher WT was defined as the first; the one with the second highest WT was the second one, and so on and so forth. The result was presented on a Gantt diagram.

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[1] DMAIC stands for Define, Measure, Analyze, Improve and Control, a Six Sigma methodology. This methodology is described in chapter 2.4.

The improvement phase contemplated the execution of this plan. Since most of actions would impact the process at medium/long term, by the end of this study only small changes were made.

1.4 Structure

The study is developed along 6 chapters, describing the context of the project and methodologies used in detail.

This chapter presents an introduction to the project, defining the problem in study, the intended objectives and the methodology used.

Chapter 2 presents a literature review of the principal concepts on which this work is supported.

Chapter 3 describes the company's business and products, the production process, and the different sections of the shop floor, characterizing the initial situation with a higher focus on the problem's description.

In Chapter 4 a variability analysis is conducted, through data collected from the production process to quantify and qualify the causes and withdraw conclusions.

Chapter 5 presents the proposed solutions to the identified problems, also referring the implementation challenges.

Last, in chapter 6, the main conclusions are analysed, and suggestions of future works are given.

2 Background

This chapter presents a brief literature review of the fundamental concepts that supported the project development.

2.1 ABC and XYZ Analysis

Nowadays, most of industrial companies have a vast portfolio of products, being the company in study an example. To define a better stock management, companies need to understand which products have the biggest impact in their strategy and which have a small significance.

Pareto's law states that 20% of the causes are responsible for 80% of the effects. According to this, in any set of products, approximately 20% of the items represent 80% of the total value. Based on this principle, the ABC analysis classifies the items into three different groups (A, B, C) according to a defined criterion. The annual cost of consumption, the annual consumption, the average unitary cost or lead-time are some examples of criteria (Flores, Olson, and Dorai 1992). The groups are defined as described below (Schuh ND):

- Products type A: a share of 20% of the products represents approximately a share of 80% total production
- Products type B: a share of 30% of the products represents approximately a share of 15% total production
- Products type C: a share of 50% of the products represents approximately a share of 5% total production

Once properly divided, the strategy for each group can be defined. Activities and efforts should be focused on A products, due to their relevance to company's results; type B, being less significant, requires less attention, but activities towards improvement should be considered; regarding C products, almost no follow-up efforts should be done (Buliński, Waszkiewicz, and Buraczewski 2013). However, ABC analysis has the following limitations, according to Dhoka and Choudary (2013):

- C items might contain critical products with low consumption value, being overlooked
- It's mandatory to periodically review and update the analysis

The ABC analysis can be complemented with a XYZ classification that classifies the products according to demand fluctuation. This is done using a statistical metric, the coefficient of variation (CV), that is given by equation 2.1.

$$CV = \frac{\bar{X}}{\sigma} \tag{2.1}$$

where:

$\bar{X}$, is the mean

σ, is the standard deviation

The groups are then defined according to the CV value as described on Table 1.

Table 1 - XYZ classification

Classification	Values	Description
X	CV < 0.75	Uniform demand, high predictability
Y	0.75 ≤ CV < 1.33	Varying demand, medium predictability
Z	CV ≥ 1.33	Abnormal demand, low predictability

When calculating the CV, one should be careful when choosing the period of analysis (yearly, weekly, daily, etc). As product life cycles are getting shorter, a yearly or quarterly analysis wouldn't be very useful. Likewise, the total period of analysis shall be defined carefully, as the number of active items proportionally increases with time (Dhoka and Choudary 2013).

According to Dhoka and Choudary (2013), XYZ analysis also has some drawbacks:

- New items frequently are classified as Z, as their demand patterns are not yet established
- It can overlook seasonal items, so it's necessary to remove these items from the analysis

The combination of the two analysis results on a matrix as the one depicted on Figure 1.

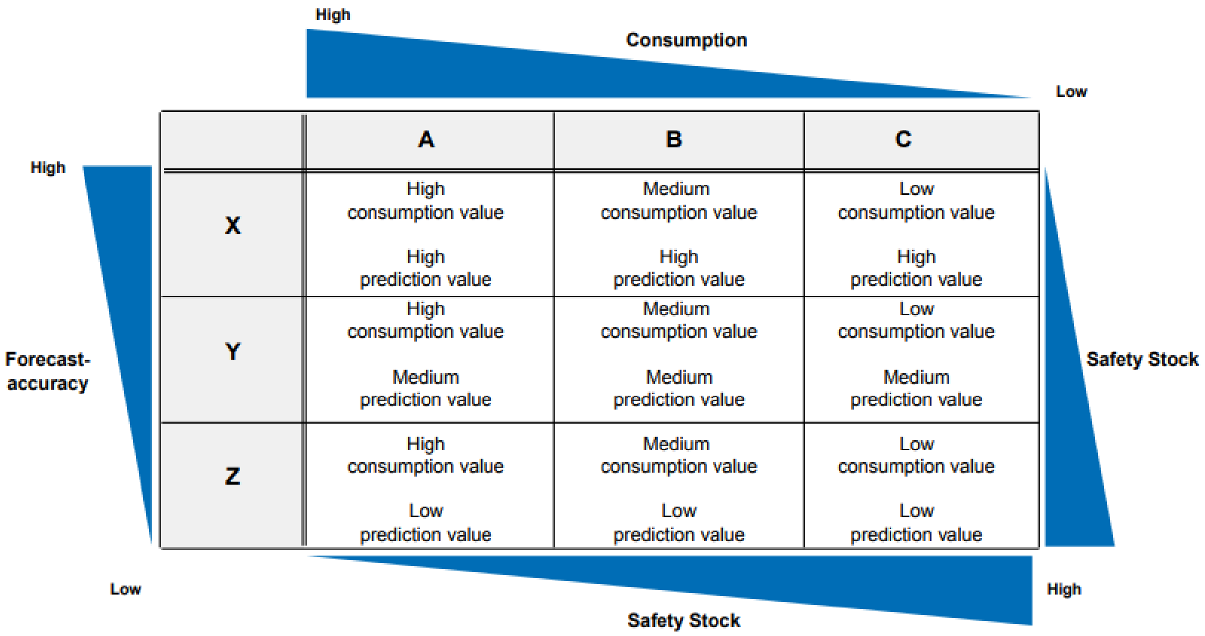

Figure 1 - ABC/XYZ Matrix (source: (Schuh ND))

This combination allows understanding the consumption of a product knowing if it is stable or not, distinguishing products amongst the same group.

2.2 Demand and Process Variability

Variability can be defined as the fluctuation of a data set around their average or mean. Being present in every process, it is important to assess whether the existent variability is significant or not, as it can lead to unmeted specifications, out of control processes and quality problems. This degradation of processes can be caused by predictable variability (consequence of a bad control, as controllable variation is the result of a set of decisions) or, in the worst case, unpredictable randomness (Hopp and Spearman 2001).

Random variability is caused by situations out of immediate control, such as customer demands. Since companies operate according to market trends, the existence of a high demand variability is of great concern, as predictions cannot be made and there's an overall uncertainty. "Unpredictable demand patterns mean the firms have to change production schedules, switch products and parts, maintain different levels of inventory, and alter throughput rates and delivery schedules more frequently and at irregular intervals" (Germain, Claycomb, and Droge 2008).

Thus, an unpredictable environment requires more organic structures. Germain, Claycomb, andDroge (2008) claim that when under this environment, companies shall have capacitated and self-sufficient units, with all the resources to meet contingencies (uncertainties where the outcomes depend partially from the environment).

But variability inside companies, this is, in production processes, can also mean complications. The existence of variation for itself doesn't necessarily mean out of control processes, so an analysis is crucial to understand if variability causes should be left to chance or be scrutiny to its root causes (Shewhart 1930). Being assessed only by statistical means, Hopp and Spearman (2001) defined the coefficient of variation (CV) as a measure to quantify variability, classifying it as low (processes without outages), moderate (existence of short adjustments) or high (processes with long outages).

On a production process, lead-time (LT) can be calculated accordingly to equation (2.2) (Hopp and Spearman 2001).

$$LT = \left(\frac{c_a^2 + c_e^2}{2}\right)\left(\frac{u}{1-u}\right) t_e \qquad (2.2)$$

where:

c_a^2, is the squared coefficient of variation of batch arrival

c_e^2, is the squared coefficient of variation of effective production time

u, is the coefficient of utilization

t_e, is the mean of effective production time

In equation 2.2 the effect of variability on lead-time is evident, as the highest its value, the longest lead-time is.

When variability is affecting lead-time, not only late deliveries might occur, leading to expedition costs, but also as early deliveries. In this case, variability causes should be properly identified and mitigated as by reducing process and product variability, better quality levels can be achieved.

To identify the proper strategies to reduce variability, it's important to understand its causes. The most common are natural variability (minor fluctuations in processes), random outages, setups, operator availability and recycle (quality problems). Although variability effects look worse at downstream processes, as it is where all sources of variability are concentrated, they are more concerning at upstream processes, since variability effects propagate through the phases of the process (Hopp and Spearman 2001).

2.3 Waste and the Lean philosophy

Lean is a methodology of continuous improvement based on the Toyota Production System (TPS), born from the attempt of Western automotive companies to cope with Asian competitors. The term "lean" was used to refer this methodology, "because it uses less of everything compared with mass production (…). Also, it requires keeping far less than half of the needed inventory on site, results in many fewer defects, and produces a greater and ever-growing variety of products" (Womack, Roos, and Jones 1991). In other words, Lean manufacturing seeks to identify sources of waste and eliminate them, to achieve better quality, focusing on what the customer needs (Dorota Rymaszewska 2014).

The core principles of lean involve the identification of what's valuable for customers, the use of "pull" mechanisms, the management of the value stream and the reduction of waste in the production system (Womack and Jones 2003).

Whilst an activity may look costly from a production point of view, it's the customer that defines what consists *Muda* (Japanese word for waste). Ultimately, value is what the customer is willing to pay for and can be added:

- Through waste reduction, usually associated with lower cost and an increased value proposition;
- By offering additional features or services valued by the customer.

Any other activity that fails to meet at least one of these requirements is considered a Non-Value-added (NVA) activity (Hines, Holwe, and Rich 2004) and, therefore, a form of waste.

According to Lean philosophy, waste has seven major causes, known as the 7 wastes:

1. **Transportation:** the movement of materials from one place to another;
2. **Inventory:** excessive inventory leads to great costs;
3. **Motion:** unnecessary movement of man or machines;
4. **Waiting:** waiting for information, deliveries, etc., which disrupts the flow;
5. **Overproduction:** produce more (or earlier) than what is needed;
6. **Over-Processing:** putting more into the product than what is valued by the customer;
7. **Defects:** quality errors require rework or replacement, wasting resources and materials.

A detailed description of the seven wastes can be found on Appendix B.

Non-utilized talent, this is, failing to properly use the skills of people within the organization, is often referred as the eight waste.

The main tools applied under lean philosophy are: Just-in-time (JIT) production systems, Kanban systems, 5S's, visual control, Poke-yoke, process standardization, workplace organization and SMED (single minute exchange of dies) (Melton 2005; Dorota Rymaszewska 2014).

Despite all the benefits of lean, one can found several references on literature about the need of properly manage change, namely, adopting lean as philosophy and not only as a methodology, focusing on empowering, helping, listening and coaching (Bhasin and Burcher 2006), considering not only the operational but also the strategic level of lean thinking (Hines, Holwe, and Rich 2004) and a shift on leadership (Dombrowski and Mielke 2014) to keep the continuous improvement process going.

2.4 Six Sigma and DMAIC methodology

Over the last decades, the focus on quality improvement lead to the existence of several new methodologies, such as Statistical Process Control (SPC), Total Quality Management (TQM), Quality Management Systems (QMS), ISO 9000, Kaizen, and Six Sigma. Having in common the objective of reducing costs and enhance customer satisfaction, they differ essentially on their emphasis and tools (Dedhia 2005).

Albeit several definitions can be found on literature review, Linderman et al. (2003) suggest that "Six Sigma is an organized and systematic method for strategic process improvement and new product and service development that relies on statistical methods and the scientific method to make dramatic reductions in customer defined defect rates", but a successful deployment of this strategy requires also behavioural insight.

Many consider Six Sigma as an evolution of TQM, since both emphasize customer input as critical to establish which processes and products need a strategic improvement and to define the attributes that are critical-to-quality (CTQ) and therefore constitute a defect (Schroeder et al. 2008). However, Six Sigma diverges from TQM due to its statistic-oriented approach, costumer focus, structured application of tools and expression of outcomes in financial terms (Goh 2002). Also, a successful implementation of Six Sigma requires an active role from top management in project definition and resource allocation, as well as extensive training of some people (Raisinghani et al. 2005), so Six Sigma can be viewed as an organization change process (Schroeder et al. 2008).

As a continuous improvement tool, Six Sigma aims to achieve maximum quality by reducing variability and consequently satisfy the customer. In fact, the sigma measures the variability or non-conformity of a process (a low sigma means low variability). Achieving a sigma level means reducing the costumer defect rate to a 3.4 Parts Per Million (PPM) or 3.4 defects occurring per million opportunities (DPMO) (Hahn, Doganaksoy, and Hoerl 2000).

The Six Sigma methodology employs different tools linked to quality management in a structured process, that is very useful in the perspective of problem solving, as it simplifies the problem by turning it into a sequence of subtasks (de Mast and Lokkerbol 2012). This process, based on the PDCA cycle, is known as DMAIC (Define, Measure, Analyse, Improve and Control). The steps of the DMAIC framework are outlined below, as described by (Pande, Cavanagh, and Neuman 2000) :

- **D (Define):** the main purposes of this phase are to identify the processes that are affected by the problem, to define precisely the project's goal and timelines, and to identify customers, their expectations and needs.

  At this point, making Problem Statement is extremely helpful to clarify the problem (What? Where? When? How big? Impact?) and a Goal Statement with the achievements to be done and definition of timeframes. Another essential tool is the Voice of the Customer (VOC), to ensure the project relates to customer requirements and understand which the Critical-to-Quality indicators are, that would be the object of analysis on the next phases.

- **M (Measure):** this phase is meant to quantify process variables through data collection from several sources. It's a transitional phase, as it serves to validate the problem and provide data to search for root causes.

  Pareto charts, histograms, and scatter plots are very useful to present the data in a more visual way to simplify the next phase – analysis.

- **A (Analyse):** the goal of this phase is to determine the root causes of problems and identify improvement opportunities.

  The major causes of variation in a process are related to six factors: Material, Method, Machine, Measures, Mother Nature and People (also known as "5M's and 1P"). In a Cause-Effect analysis, where the problem is the "Y", these factors are the "X's" that appear on the branches of a Fishbone Diagram (Figure 2).

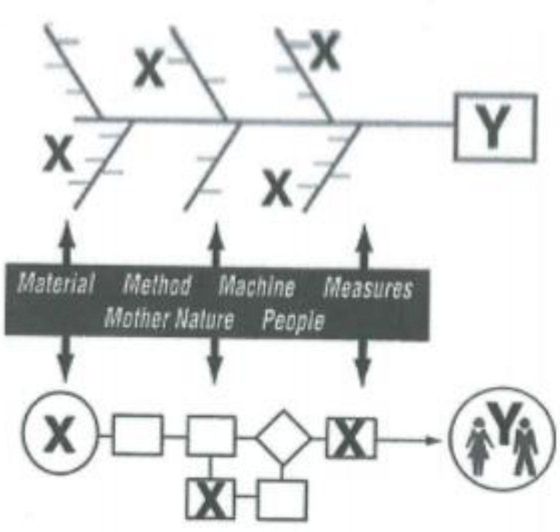

Figure 2 - Example of cause and effect diagram and process map identifying the X's of effect Y (source: (Pande, Cavanagh, and Neuman 2000))

A root cause analysis implies that all the X's shall be analysed, targeting "the vital few" that contribute the most for the problem.

- **I (Improve):** this phase has the purpose to evaluate and implement improvement actions for each problem through a well-structured improvement plan.

  Brainstorming sessions are quite useful in this phase, as they bring the expertise of people to the table and provide various and creative solutions to the problems. After, there's the need to narrow the options and plan their implementation. Also, in this phase is where the proposed solutions are tested (Design of Experiments is one of the most used tools), and new measurements are done to quantify the results and assess the improvements success.

- **C (Control):** once the improvements were done, there's the need to define long-term actions to maintain them.

  Documenting changes and new methods with a process for updates or reviews, build a Process Response Plan to act if anything goes wrong, select indicators to monitor performance and document them are the most common steps in this phase.

De Koning and De Mast (2006) proposed a reconstruction of the DMAIC methodology, more precise and consistent, divided by steps (which indicate the actions to perform or the intermediate results to be achieved) and phases (a group of steps). This reconstruction is summarized on Table 2.

Table 2 - DMAIC phases and steps (according to De Koning and De Mast (2006))

Define: problem selection and benefit analysis

- **D1.** Identify and map the relevant processes
- **D2.** Identify stakeholders
- **D3.** Determine and prioritize customer needs and requirements
- **D4.** Make a business case for the project

Measure: translation of the problem into a measurable form, and measurement of the current situation; refined definition of objectives

- **M1.** Select one or more CTQ's
- **M2.** Determine operational definitions for CTQ's and requirements
- **M3.** Validate measurement systems of the CTQ's
- **M4.** Assess the current process capability
- **M5.** Define objectives

Analyse: identification of influence factors and causes that determine the CTQ's behaviour

- **A1.** Identify potential influence factors
- **A2.** Select the vital few influence factors

Improve: design and implementation of adjustments to the process to improve the performance of the CTQ's

- **I1.** Quantify relationships between X's and CTQ's
- **I2.** Design actions to modify the process or settings of influence factors in such way that the CTQ's are optimized
- **I3.** Conduct pilot test of improvement actions

Control: empirical verification of the project's results and adjustment of the process management and control system in order that improvements are sustainable

- **C1.** Determine the new process capability
- **C2.** Implement control plans

2.5 Lean Six Sigma

The two continuous improvement methodologies described in sections 2.3 and 2.4 diverge in many ways.

While Six Sigma aims to improve process performance and achieve high levels of quality and low variability, Lean focuses on seeing the process and the entire value stream from the perspective of the customer; a specific and well-trained group of individuals develops Six Sigma, with a high cost, while Lean involves the entire organization, empowering employees, and presenting results faster. One is driven by the production viewpoint, while the other is more customer oriented.

As both Six Sigma and Lean, despite their success, have limitations, many claim that merging the two philosophies is best, adopting a Lean Six Sigma (LSS) philosophy instead. The potential of this method is shown in Figure 3, comparing LSS, Lean and Six Sigma.

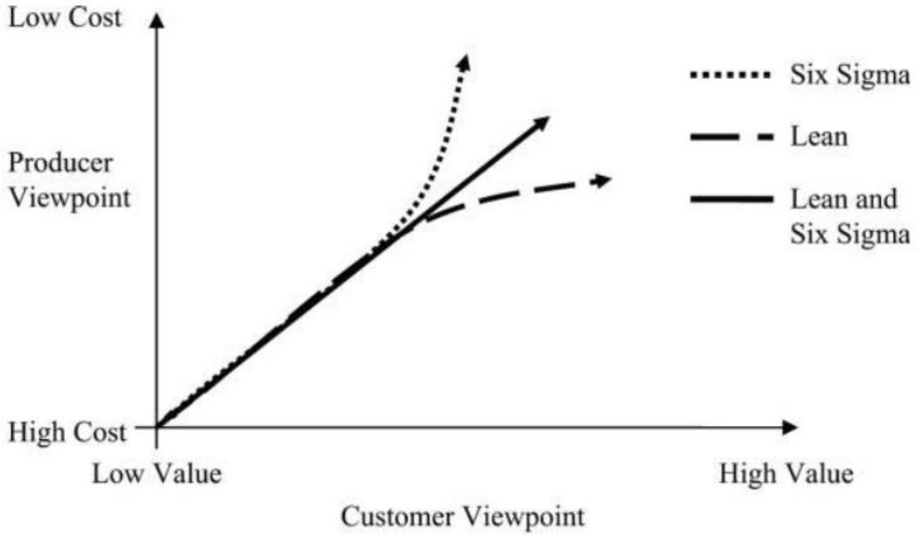

Figure 3 - Comparison between Lean, Six Sigma, and Lean Six Sigma (source: (Arnheiter and Maleyeff 2005))

LSS provides an equilibrium, avoiding the extremes, i.e., having rigid responses to the market and impacting the value creation (extreme Lean) or concentrating too much on reducing variation and making improvements, beyond costumer requirements, and wasting resources (extreme Six Sigma) (Pepper and Spedding 2010).

Salah, Rahim, andCarretero (2010) define LSS "as a methodology that focuses on the elimination of waste and variation, following the DMAIC structure, to achieve customer satisfaction with regards to quality, delivery and cost. It focuses on improving processes, satisfying customers, and achieving better financial results for the business".

The main benefit, according to Pepper and Spedding (2010), is that "lean tools and techniques identifies key areas that can be leveraged by Six Sigma techniques", as Six Sigma provides the tools to leverage improvement and Lean is responsible for the strategy and structure to apply them. Snee (2010) goes further, claiming that a Six Sigma project might provide the identification of quick hits (projects rapidly accomplished and with little waste of time or resources in case of failure) or Kaizen projects (rapidly improvement projects, with maximum duration of 30 days). In a similar way, Lean projects may reveal a quick fix or a problem without known solution, generating then a Six Sigma project.

Having a lot of common tools (Figure 4), the choice of the appropriate ones on a LSS project is related with the problems identified and the root causes to be pursued.

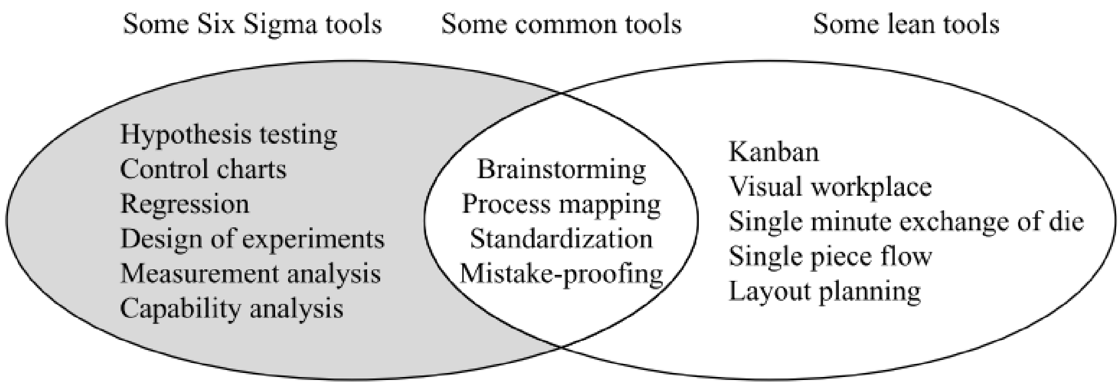

Figure 4 - Example of Lean and Six Sigma common tools, (source: (Salah, Rahim, and Carretero 2010))

Being so, on a LSS project, many companies use the two methodologies in parallel or intercalated. However, Salah, Rahim, andCarretero (2010) argue that the most efficient way to implement a LSS project is to draw on both simultaneously to obtain the maximum benefit, having proposed an integration model relating the phases and tools of both with DMAIC as its core structure.

3 Case Study

In this chapter the problem is presented in a more detailed way. To better understand the object of study, it’s also presented a description of the products and the production process.

3.1 Characterization

The company in study operates in the fields of Industrial Automation and Mechanical Engineering, manufacturing conveyors, palletizers, and industrial equipment, and providing robotic solutions and automation software.

Therefore, it’s important to make a distinction between the two core businesses: manufacturing of products and design of industrial solutions.

The design of industrial solutions or special projects (as denominated in the company) work under an Engineering-to-Order (ETO) model. These projects have a long duration, as they are done from scratch according to customer requirements and several modifications and testing are needed (see Appendix C).

On the other hand, in a daily-to-daily basis, the company manufactures parts for industrial conveyors (denominated as Standard Products). These productions follow a hybrid strategy, in a mix of Make-to-Stock (MTS) and Assemble-to-Order (ATO): products with a higher lead-time or with a high supplier delivery time are produced according to a minimal stock and the other products are assembled when there is an order, with the parts that are kept in stock.

Standard Products are done with two different purposes: either for a direct sale or for a project. In the first, the client buys just the products, separately; in the latter, distinct from Special Projects, the client buys the products and the workforce to install them in their facilities.

Though Standard Products have a more structured process, they still are very complex products, as they go under several different operations, include several parts, and have a challenging assembly.

Figure 5 presents an example of a standard product and Figure 6 schematizes the assembling of its components (concerning assembling, this is considered the less complex product manufactured).

Figure 5 - Example of a standard product: conveyor

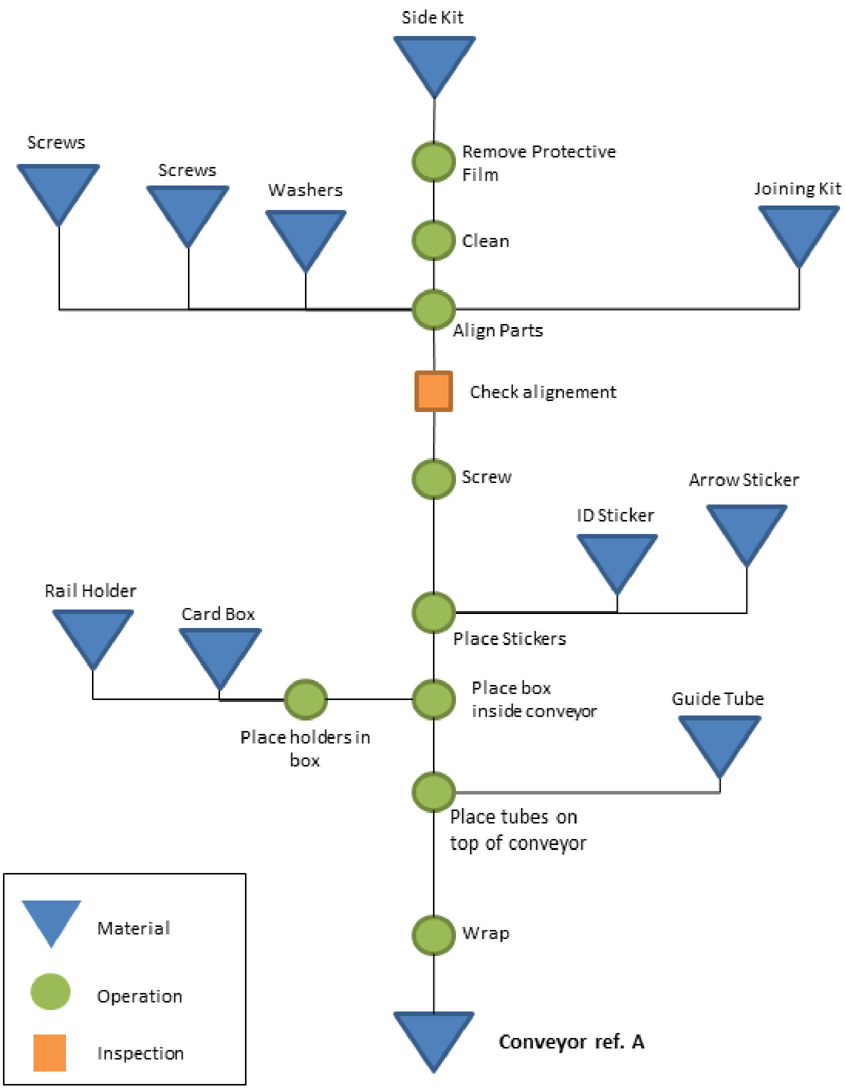

Figure 6 - Gozinto graph of the assembling of a straight conveyor (reference A)

All Standard Products are divided into different families, according to their function: conveyors, wheel curves, switches, adjustable conveyor links, belt brakes, package traps, chain tensioners, transfer units and hose breaks.

Giving the administration's goals, this study regards only the production of Standard Products, its processes and how can they be improved.

3.2 Production Process

The production process consists in four major operations: cut, fabrication, pre-assembly, and assembly. Each operation has a distinct place on the shop floor, as shown in Figure 7.

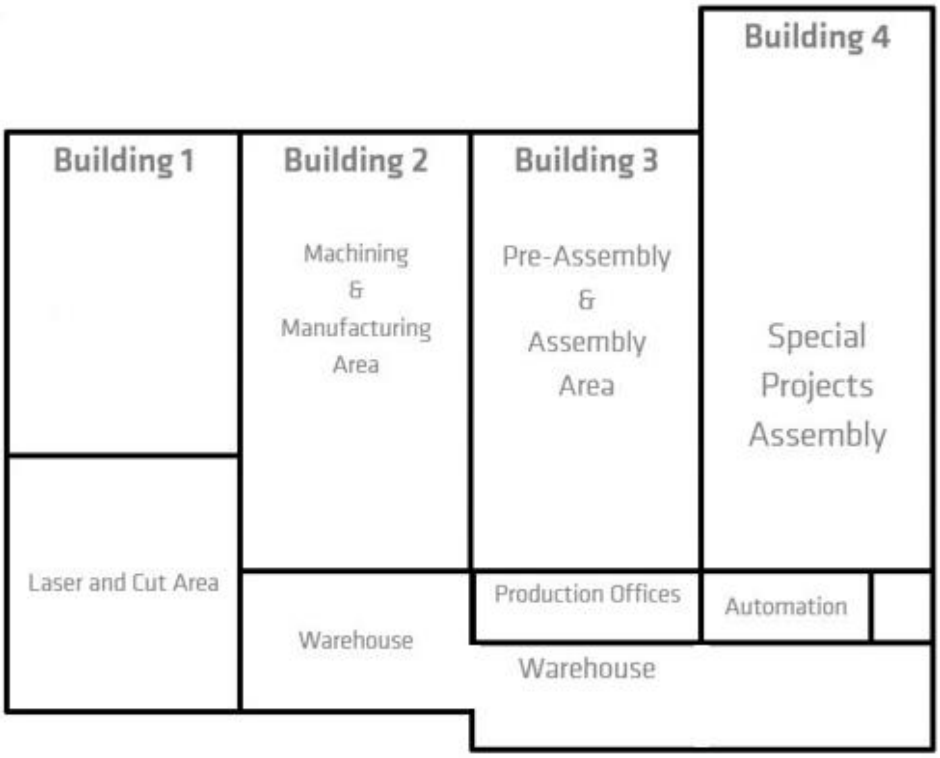

Figure 7 - Representation of shop floor areas

Despite having well defined operations, it's not a linear process, in the sense that the manufacture of a product doesn't necessarily include all operations. For example, a product may not need to have materials cut, so its production process starts with fabrication; as the company works under an ATO strategy, some products just need to be assembled, thus the production order (PO) is just for that operation. This particularity is best shown in the Value Stream Map (VSM) presented in Figure 8.

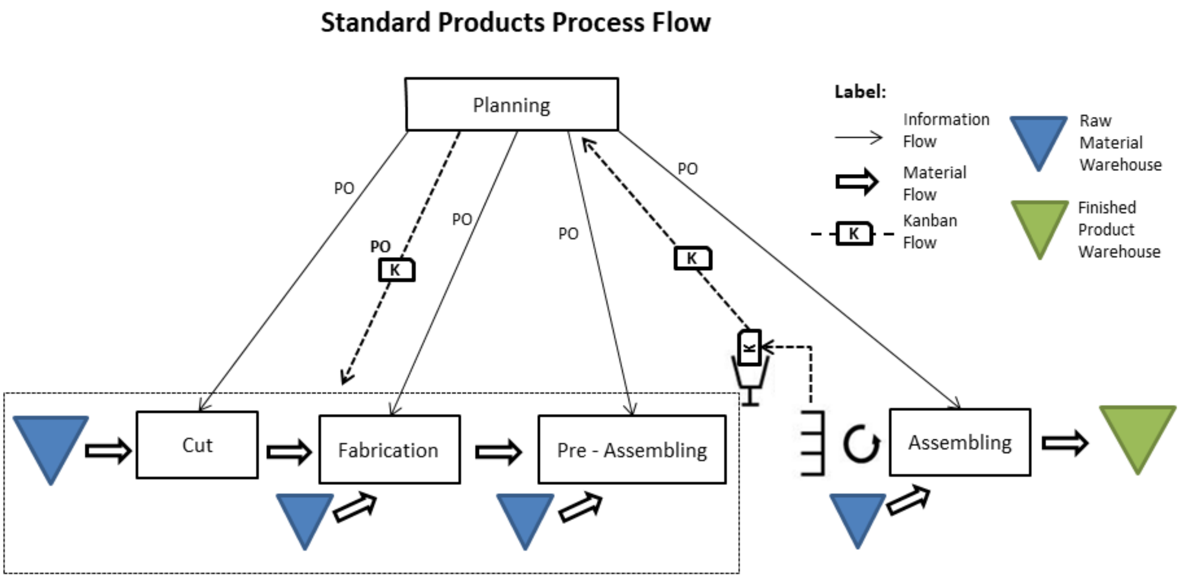

Figure 8 - VSM of Standard Products Flow

The process starts when a production order is released. The PO can be either to cut, to fabricate, to pre-assemble or to assemble. The material for each operation comes from the previous one and/or from the main warehouse. Once the product is assembled, it goes through a final inspection and it's wrapped and sent to the warehouse for stock or expedition.

As represented in Figure 8 the process contains a Kanban system. This system is implemented just for the parts that are frequently used in the assembling phase. Once the minimal quantity of a part in the supermarket is reached, the respective Kanban cards are sent to planning, that then issues the order to produce more parts. After going through the necessary processes, the parts are pre-assembled and transferred to the supermarket.

As for warehouses, although there's just one represented on the plant layout, there are four different types of warehouses, with different functions (Table 3).

Table 3 - Types of warehouses at production

Number of Warehouse	Designation	Main Function
1	Main warehouse	Storing raw materials and finished products
7	Border Line	Keep small pieces (screws, for example) on the assembly stands
8	Supermarket	Store Kanban components
10	Shop Floor	Temporarily store the parts between different operations (applies only to Work in Progress, WIP)

Each product (that has a unique reference code) has a defined bill of materials (BOM) that contains a list of all components needed, as well as the order of the required operations and an estimation of production times (usually referred as Bill of Process, that in this case is incorporated in the BOM). An example of a BOM can be found at appendix D.

As understanding the production process is vital to the problem in study, a more complete description of each operation is given.

Cut

This operation is performed in two different ways according to the part needed: pipes and rods or steal sheets.

Raw material for pipes and rods is kept on the main warehouse and once a production order is released it is transferred to the workstation. There, it is cut on an industrial saw according to the requirements of the PO.

As for steal sheets, they are stored on a specific space at building 1. When production starts, the worker gets the sheet with the specifications required (thickness, for example), and places it on the laser cutting machine. After they are cut, these parts are worked on a sander machine or manually on a grinding wheel (when they are too small) to soft the edges. The protective film is not removed from sheets in any phase, to prevent scratches when storing the parts.

Once the ordered parts are produced (either sheets, pipes or rods), they are placed on a pallet and moved to the destination by the logistic operator.

Fabrication

Fabrication includes several different operations: bending, milling, turning, and welding.

This part of the process varies a lot giving the product, so there's not a sequence of operations common to all. Some parts just need bending, others just need milling or turning, while others need more than one different operation. Giving the high number of diverse parts produced and all the possible combinations of operations, this part of the process will from now on be referred as fabrication (except when explicitly talking about a specific operation). Though, in every workstation there's a specific area for products to be processed and for products already processed. These products are managed by the logistic operator, who's responsible for deliver the parts to the processing workstation and then collect them and take them to the next station.

Pre-assembly

The pre-assembly process consists on the assembly of components that are common to many final products or products that are frequently produced, being the product stored on the supermarket or on the main warehouse.

This process is similar to the assembly process, but only concerning the assembly of small parts with the mainly purpose to feed the supermarket.

Assembly

The assembly process is the most complex one.

When assembles are ordered, all the materials are placed on the material entrance side of the assembly stand. The worker then opens the file with the 3D design of the part and starts to assemble all the components. Once this is done, the assembly section's responsible inspects the products and if the products have no defects, the worker wraps them and places them on the finished products side of the balcony to be transferred to the warehouse by the logistic operator.

Each assembly stand in the assembly section is designed to assemble a certain type of product: there are two assembly stands to assemble conveyors and adjustable conveyors, three for wheel curves, two for drive units and transfer units, two for switches, belt brakes, package traps, chain tensioners and hose breaks. Each assembly stand has only the tools needed to assemble the corresponding products, identified by colours and with an identified place for each tool. Also, there are three lights (blue, yellow, and red) in each assembly stand, with the intent to signal the situations described in Figure 9.

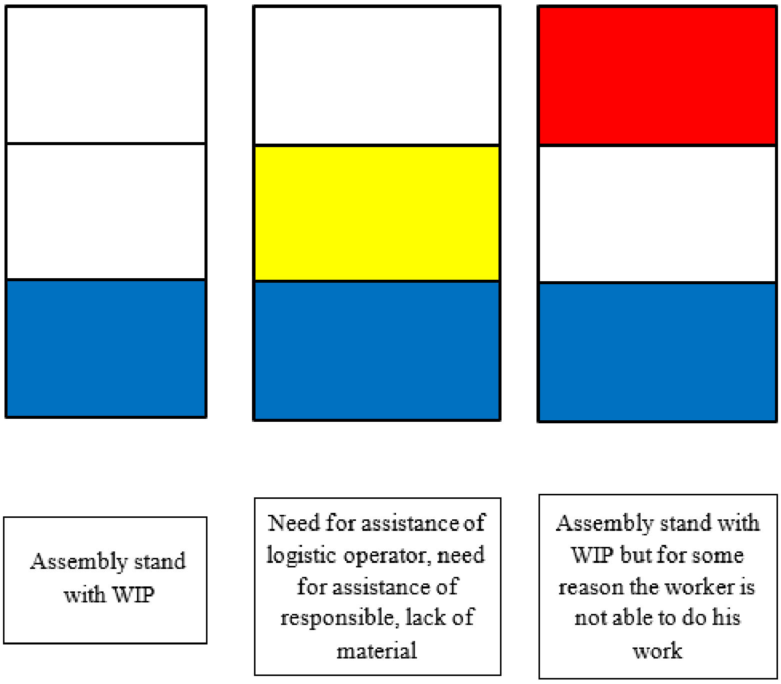

Figure 9 - Light colour code and its meaning

3.3 Problem Description

The company in study is known to be very flexible as it is able to manage the work in progress to satisfy new orders and still meet deadlines with other clients. To be successful, a correct definition of production lead-times is needed so production planning can assure the products being delivered on time.

Variability occurs in two distinct ways: the variability of production times, which consists in the difference between total production times of a product, and the variability of time between the releasing of a production order and the conclusion of the product (when the production order is closed). As the latter is dependent from many different variables (for example: number of special projects in parallel, deadlines of products, number of workers) and can be mitigated with better planning (for which is essential a correct definition of production times), this study investigates the reasons that cause production time variability.

An ABC/XYZ analysis (appendix E) was conducted to know which products had the greatest impact on production quantities and production costs and therefore would be the basis for this study. This analysis considered the data from a period of one year, prior to the beginning of this study. In total, 329 products were analysed. References classified as A and with the greatest produced quantity within each family were chosen to this purpose and are depicted on Table 4.

Table 4 - References selected for production analysis

Reference[2]	Type of Product
A	Conveyor
B	Wheel Curve
C	Package Trap
D	Adjustable Conveyor
E	Chain Tensioner
F	Belt Brake
G	Drive Unit
H	Transfer Unit
I	Switch
J	Hose Break

Currently, production lead times are defined by the technical department when creating the bill of materials for a product. The company also has a computer system that allows the workers to register when they start and end an operation of a production order, so the production time of each operation is registered. However, as the examples in Figure 10, Figure 11, Figure 12 and Figure 13 show, there's a high variability of times registered in the system versus the time estimated on the BOM.

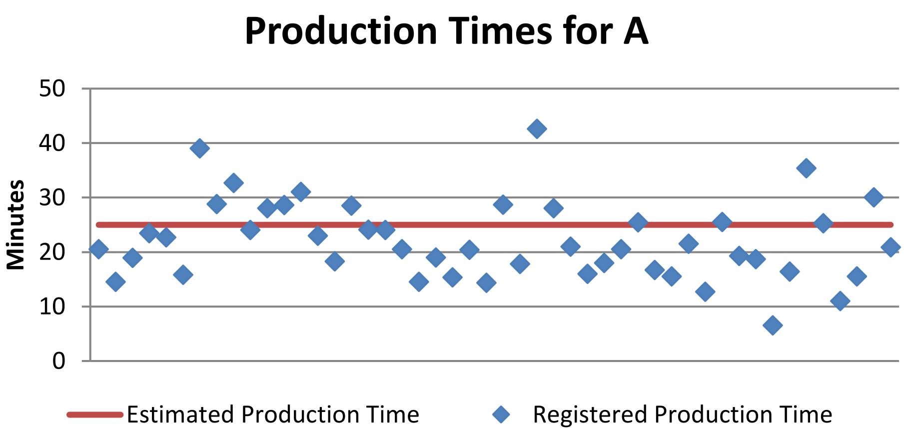

Figure 10 - Production time variability of reference A (historical data)

[2] For confidentiality reasons the real references are not mentioned.

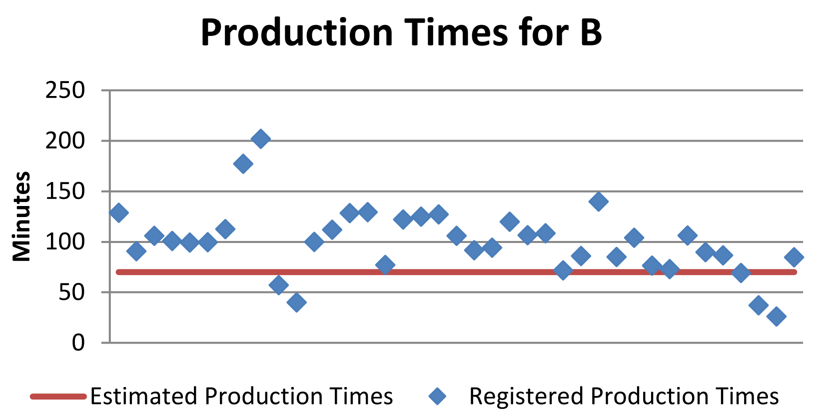

Figure 11 - Production time variability of reference B (historical data)

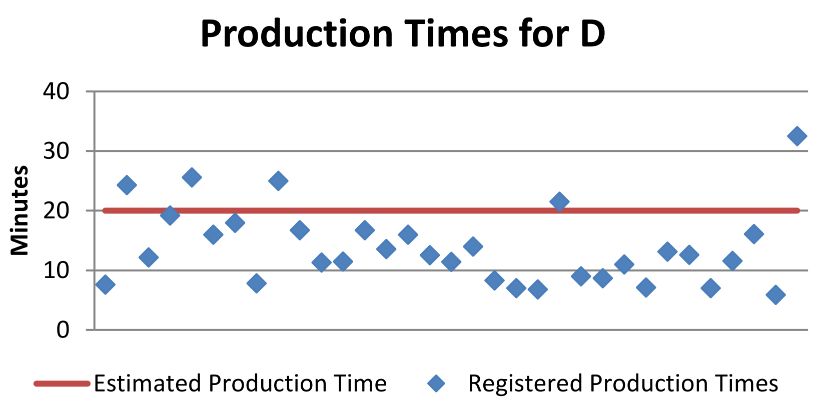

Figure 12 - Production time variability of reference D (historical data)

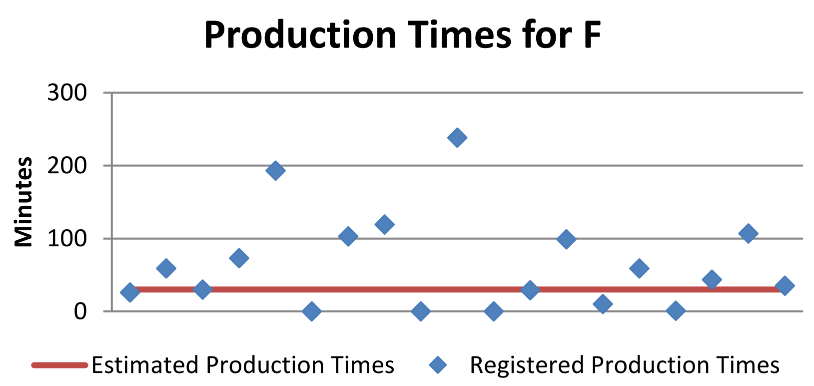

Figure 13 - Production time variability of reference F (historical data)

The existent variability has a great impact on production planning, aggravated by the need to also produce to ETO projects, and often leads to one of two situations:

a) The company is unable to meet the deadlines

b) Production workers need to work extra-time to meet the deadlines

This has a significant financial impact either by leading to unsatisfied customers or by the higher cost of handwork on extra hours.

The main objective of this study was to quantify the variability and qualify its causes for one product of each of the ten families. Since it was not possible to collect enough data for each reference in the period of this study to perform a statistical analysis, the study was focused on the overall process and not on specific products.

3.4 Synthesis

This chapter provides a characterization of the company and the problem in study. Operating in the field of industrial automation, the products manufactured are of great complexity, as they go under several operations: cutting, bending, milling, turning, welding, and assembling.

As the production process consists of several steps, the variability affecting the entire process easily increases, making it difficult to obtain correct lead-times and leading to extra costs.

The analysis of the production process and existent variability, as well as its causes, is presented on chapter 4.

4 Variability Analysis

To define the most adequate improvement actions is essential to perform an analysis of the production process, understanding its complexity. The Measure and Analyse phases of DMAIC supported this purpose.

4.1 Demand Variability

Despite being extremely difficult to take any actions to reduce this type of variability, as it is an external factor to the company, it is important to be aware of its impact on total variability.

To understand the effects of demand variability, an XYZ analysis was done. The analysis contemplated the weekly quantities produced [3] of each final product reference over a period of 1 year prior to this study.

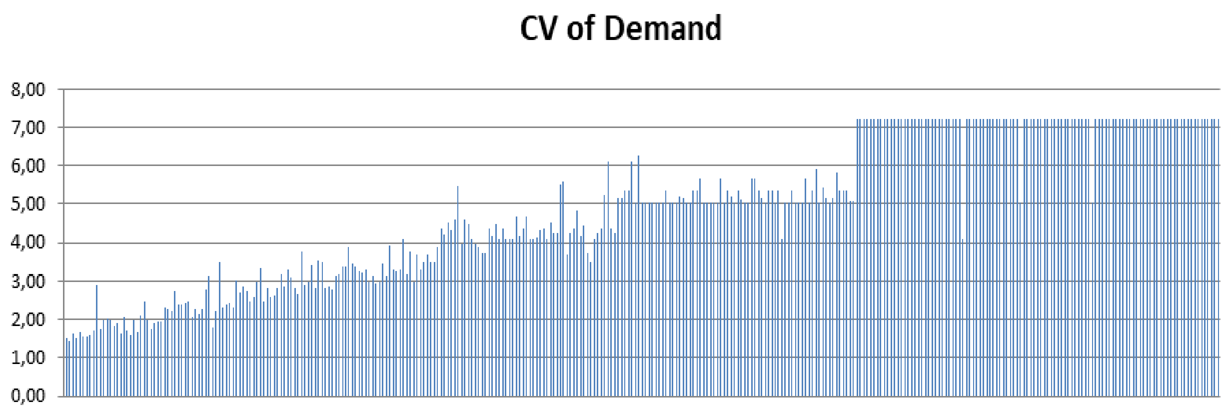

Figure 14 - Coefficient of Variation of demand

As shown in Figure 14, the coefficient of variation of demand (Y axis) is significantly higher than 1 to all references in analysis (X axis), being classified as Z, endorsing the high variability of clients' orders. This means that the demand is so unsteady that it is impossible to make forecasts, making the need of safety stock obligatory.

Another important aspect of demand is the ordered quantity. Giving the existing data, another CV was calculated, considering only the weeks with production. In this way it was possible to analyse the variability of ordered quantities, represented in Figure 15. In this case, almost all references presented a CV lower than 1 (in some was 0, as there was just one order in the analysis period), meaning that despite not being possible to predict when there would be an order, the quantities ordered each time are similar.

[3] Giving the structure of the informatics system, it was not possible to collect data based on clients' orders. But since the production of a reference is always associated with an order or sale, production quantities were utilized to quantify the demand. The only side effect of this fact is the possibility of a gap between the week the PO was released and the week the client ordered it.

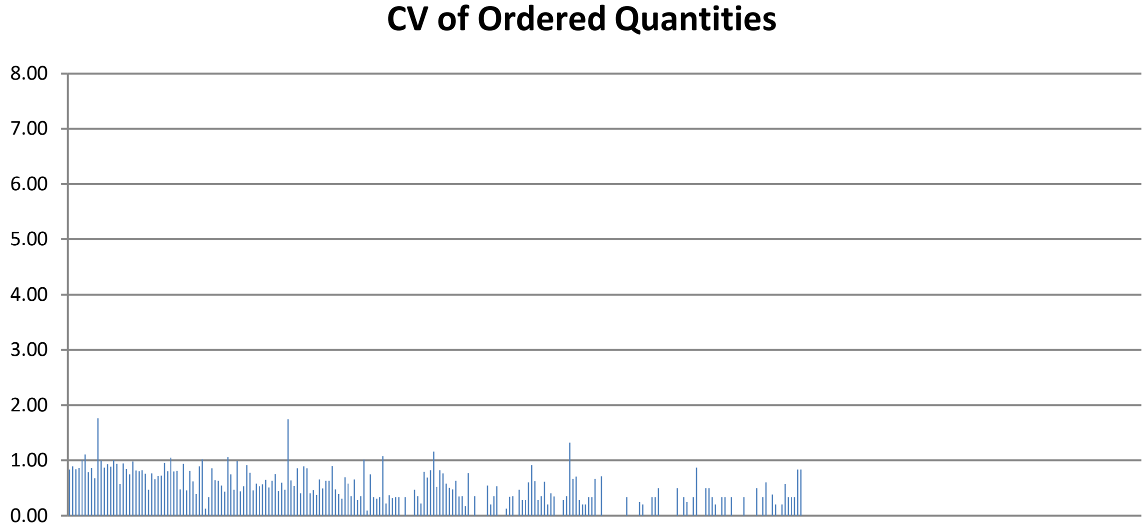

Figure 15 - Coefficient of Variation of ordered quantities

Giving the high variation of demand and the impossibility to act over it, it is even more important to reduce the variability of process time to decrease the overall variability.

4.2 Lead-Time Variability

Lead-time concerns the total amount of time necessary, in terms of work, to produce a specific product. As stated on the previous chapter, the production process of the company in study was under high variability.

To quantify this variability, the objective was to track production orders for the products selected (already presented on Table 4). However, giving the high demand variability described in 4.1, there were not sufficient production orders for all references during the time contemplated by this study to make a proper statistical analysis.

Nevertheless, some production orders were followed through direct observation, registering production times and occurrences that could lead to variability. To understand if there was in fact variability, production times registered were compared to the estimated time of production and with each other. This procedure concerned only the assembly process, for several reasons:

- Due to the flexible planning of production, there can be a long time between the releasing of the production order and the completion of the order, as orders with tightest deadlines have priority;
- Some orders followed have already been processed in cut and fabrication, not being possible to measure these production times;
- For more complex products, it was not feasible to follow the entire processing of all parts, as just the assembly of one unit can take more than one day.

Despite the quantity order being usually higher than one, it was not possible to consider each product as a sample, as workers do a specific step of the assembly in all the parts and do not process them one by one (for example, cleaning all the pieces that need to be clean instead of cleaning one piece and assembly the entire product), being impossible to measure the exact time of each one. Instead, the total amount of time was registered, and it was calculated the medium production time of a unit, with each production order representing one sample.

For the given reference of conveyors, the different production times per product are represented in Figure 16. More detailed information about these times and other times observed can be found on appendix F.

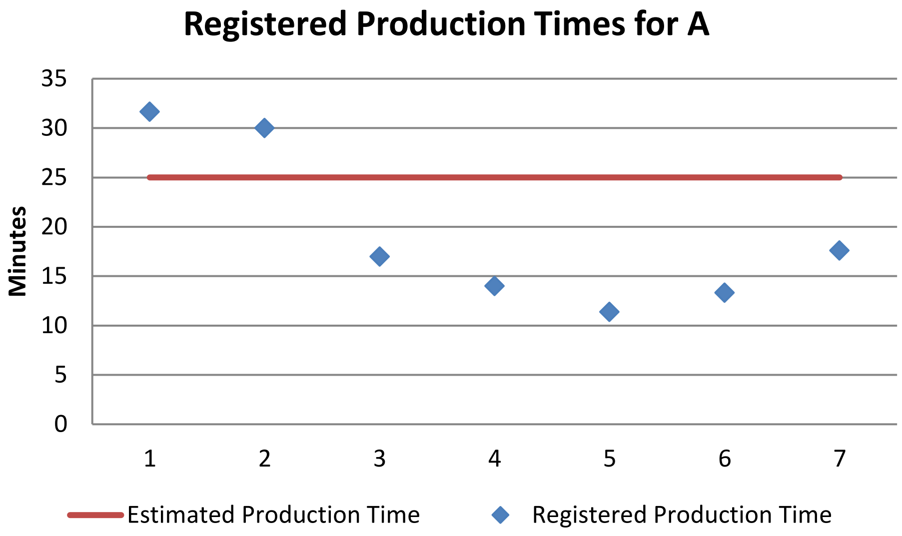

Figure 16 - Observed assembly times per product of conveyor A

As it is possible to see, there's a significant gap between the estimated and real production times (in fact, all samples fall off the interval of a 10% deviation from estimated time) and even between the samples (the difference between the maximum and minimum values is 20.29 minutes/product). The calculated CV of these times is 0.39, confirming that there is significant variability on this process.

It's important to note that these values represent the variability of the isolated process of assembly (the last a product must go through) and that variability effects of operations propagate through the entire production process, which aggravates the problem and degrades the entire performance of the production process.

Since the number of samples taken regarded just the assembling process and weren't enough to withdraw conclusions about the entire process, historical data from the system, for the period of 1 year prior to this study, were collected.

Intending to know if the process was under control, the historical data collected was used to build control charts. The control charts used were the Individual Chart (I) to plot individual observations as separate data points as there is no rational subgrouping (therefore the subgroup size is =1) and a Moving Range (MR) chart to plot the difference between data (Figure 17).

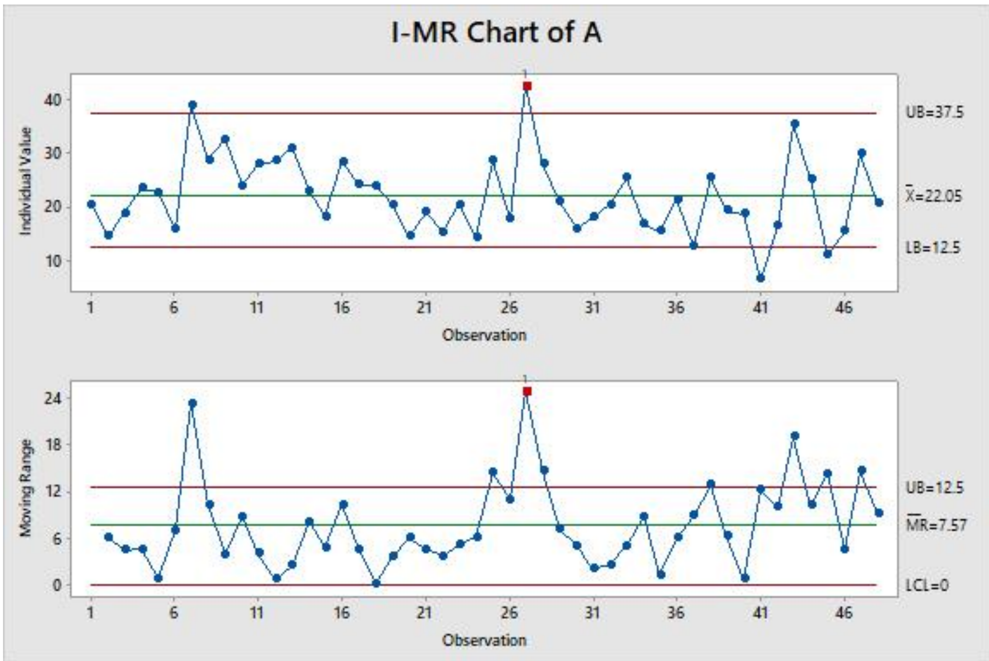

Figure 17 - I-MR chart of production times of reference A

For the moving range chart, the upper bound defined represents 50% of the estimated time, meaning that would be the admissible difference between two production orders. Even with a considerable margin of variation, 8 points fall over the upper limit, one of them even falling out of the 3σ interval, meaning that the process variation is not under control. Regarding the I chart the upper and lower bounds were defined admitting a maximum deviation of 50% (above or below) from the time estimated (25 minutes). As expected, some points fall off the defined interval, as the process variation is not under control.

As the control chart was calculated only for one reference, it was necessary to check if this was not an isolated case and if, in fact, the entire process was under high variability. To allow comparisons between different products and references, instead of the production times, the percentages of deviation towards the estimated time were used. If there was not significant variability, the percentages should not be very high or different. Nevertheless, when plotting all data, the result was unexpected, as seen in Figure 18.

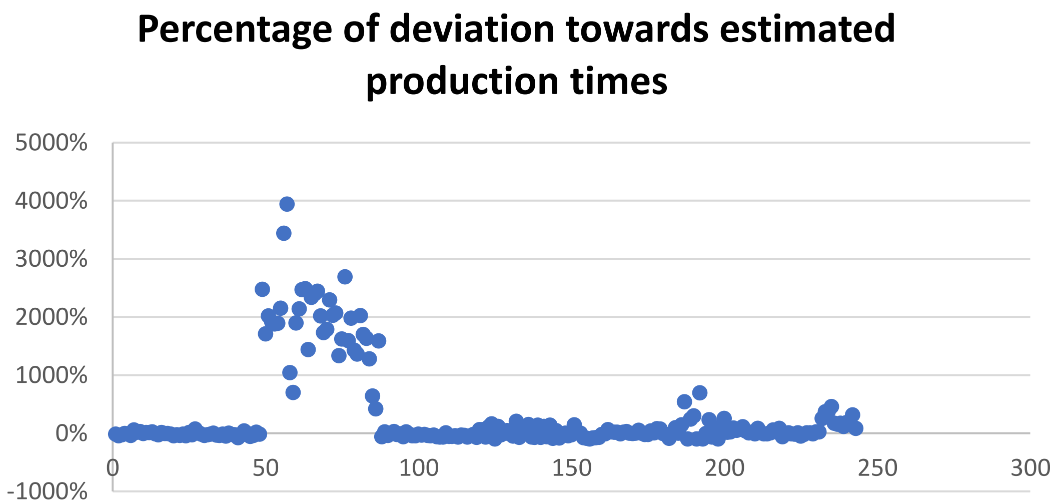

Figure 18 - Scatterplot of percentage of deviation of production times towards estimated times

Not only the values were very scattered but also there are several points with a deviation superior to 500% of the estimated time. Only two factors could cause such high values: either the process was completely out of control or registrations were not being done properly. Since the first seemed unlikely, the data in the system correspondent to the productions orders that were followed and measured was collected. Comparison between real times and times registered in the system is presented in Figure 19.

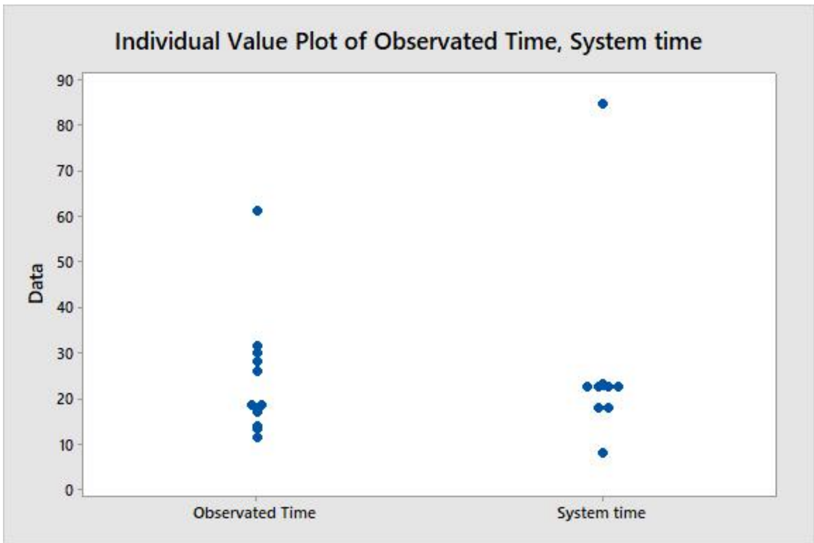

Figure 19 - Comparison between production times observed and production times registered on system

In fact, the times registered on the system do not match reality, with deviations ranging between -55% and 86%, leading to the conclusion that the data from the system are not reliable and therefore cannot provide real production times and allow variability quantification.

While observing the assembling process, besides the measurement of production times, all occurrences were registered to further analysis. Also, while helping on a parallel study of the administration, it was possible to identify variability causes in the upstream processes. Factors observed were registered and potential causes and solutions were identified, resulting in the Cause-Effect diagram in Figure 20 and the Pareto chart in Figure 21 .

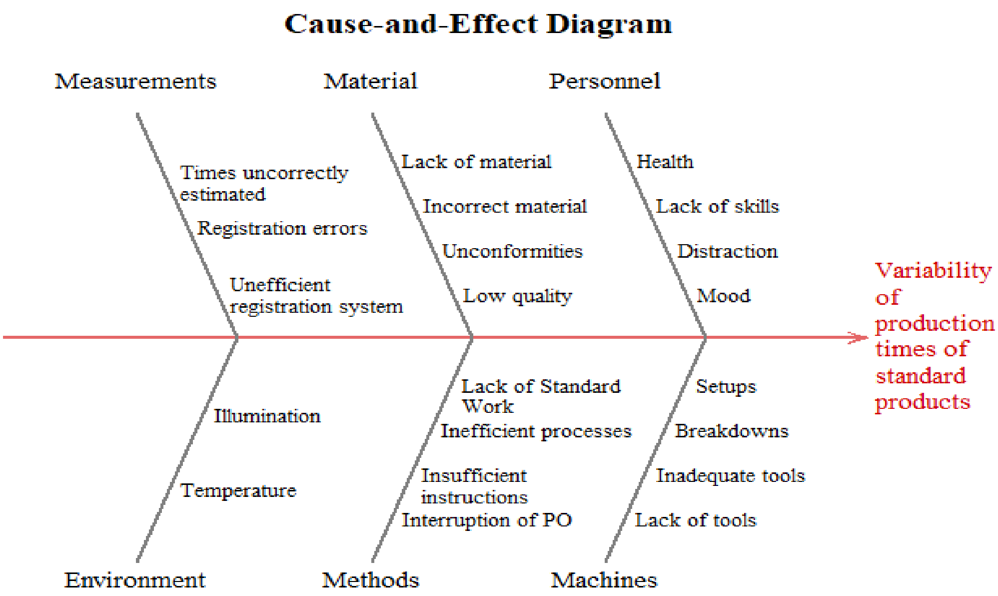

Figure 20 - Cause-and-effect diagram: Variability of production times of standard products

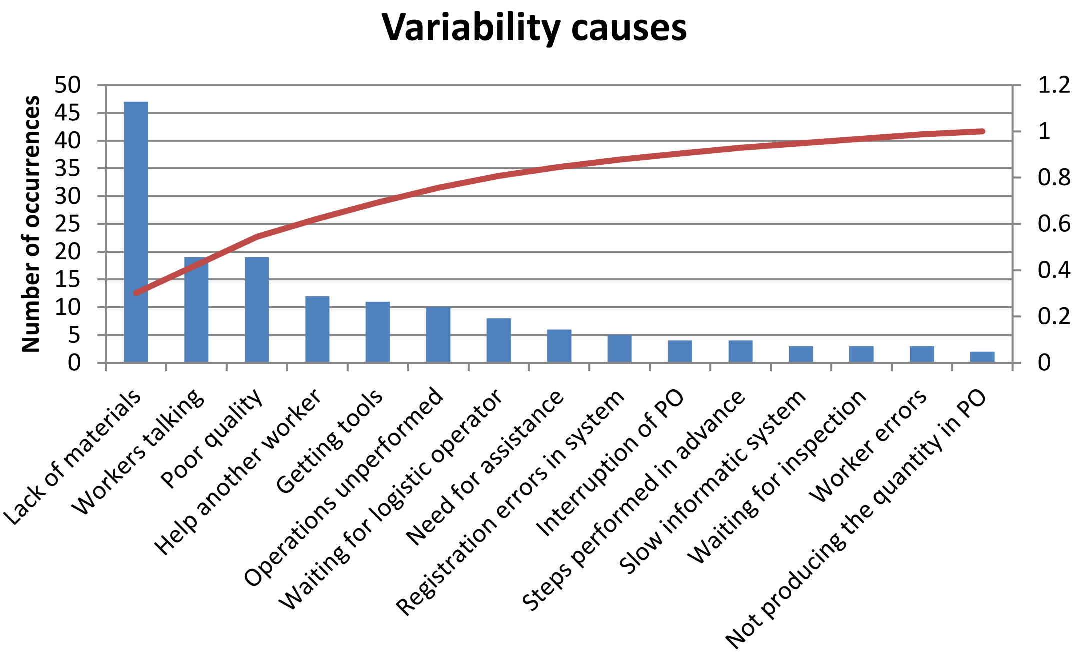

Figure 21 – Pareto chart of variability causes identified

In a brainstorm session, the most critical to quality causes in terms of variability considered were:

- Constant lack of materials due to a poor coordination between the production department, shop department and warehouse;
- Materials missing for a PO already in course, when received by the warehouse, were stored on the electronical warehouse without warning production. This led to situations like "receive-put in warehouse-remove from warehouse", wasting time, or even production being waiting, until the moment the deadlines were in jeopardy, for materials that have already arrived;
- Incorrect separation of materials by the logistic operator, which is still in the learning process and hasn't had the proper formation;
- Lack of proper tools;
- Slow software system, especially when starting, taking too much time for workers to change the number of the PO or inserting the quantity produced;
- Insufficient number of computers, leading to unnecessary motion and workers interrupting the work of others to make registrations;
- Inefficient ways to move and wrap large and heavy products;
- Operations like threading and countersink unperformed, implicating the worker interrupting the process, leave the workstation to perform those operations and return;
- Low quality of materials or unconformities not detected, leading to rework or need of extra time to perform the operation.

4.3 Production Process Waste Quantification

According to Snee (2010), the root causes of poor performance can be related to material and information flow between processes or to the value adding transformation of the process itself;

but this should not be analysed separately, as often flow problems can cause poor transformation processes and vice-versa.

A good approach to better address the root causes is then to look not only at the processes, but also to what happens between them (Figure 22), developing a good and functional model in the form of Y= f(X) (Snee 2010).

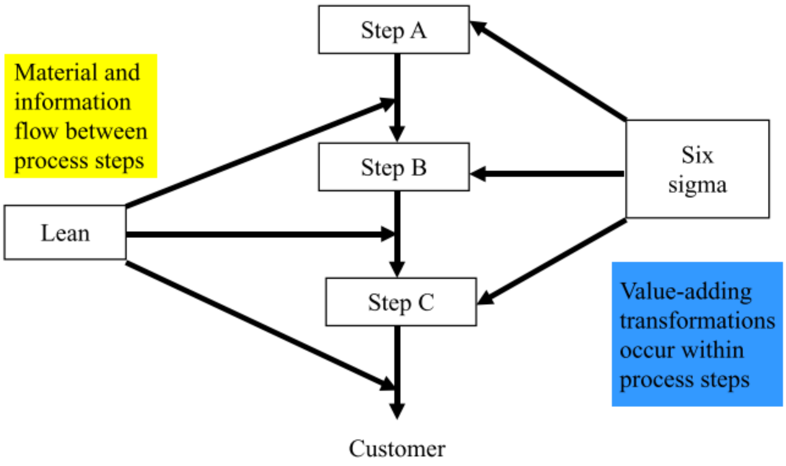

Figure 22 - Improvement opportunities on a process (source:(Snee 2010))

Following this philosophy, the entire process was analysed also with the intent to quantify waste.

While on the shop floor, it was possible to observe that there was a lot of *Muda*. Since the main goal of this study was to improve process performance, it was decided that this was a problem that also needed to be addressed.

As so, it was compulsory to quantify the amount of waste in the process, i.e., the amount of NVA activities. At first sight, excess of motion appeared to have a lot of significance, so it was measured separately.

Excess of motion

Every workstation is provided with the tools needed for the job and parts to be processed are brought to the workstation by the logistic operator, so motion shouldn't represent a problem. However, several days on the shop floor revealed quite the opposite – there was clearly excess of motion.

To understand how big the problem was, all movements from workers were registered, namely the origin and destination of the movement. During this time, an average of 80 movements per day were observed (a significant number given the medium size of the company and the number of workers on shop floor, about 35).

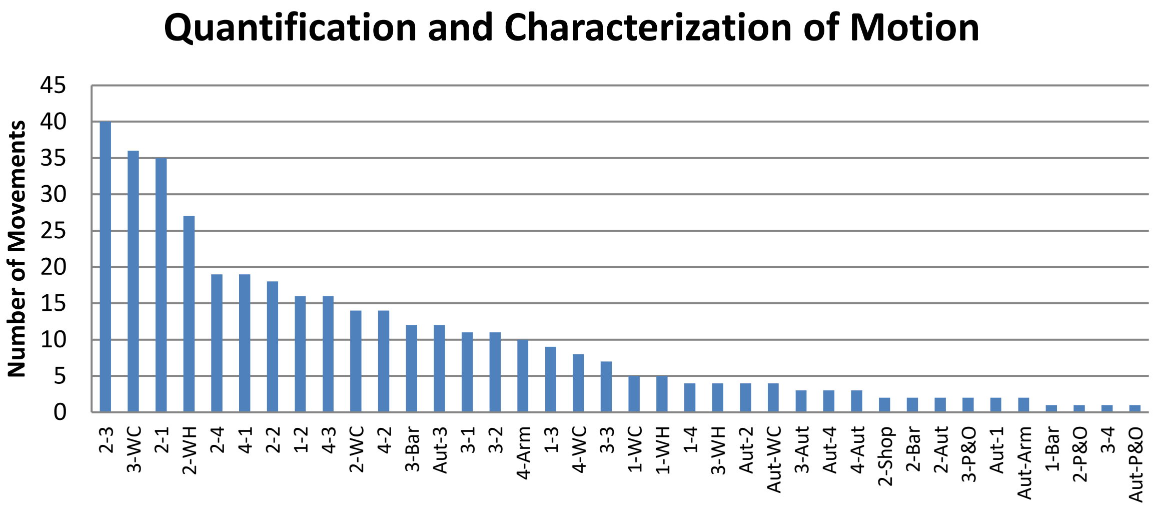

Figure 23 - Quantification and characterization of motion

Figure 23 shows the quantity and type of movements, during a period of 6 days, registered in the form of "origin-destination". For example, "2-WH" represents a movement from a worker, whose workstation is in building 2, to warehouse (WH) whereas "3-3" represents a movement within the same building (despite being part of building 4, Automation was considered separately to simplify the analysis).

This leads to a significant loss of time, not only because the excessive number of movements, but also because the dimension of the shop floor, aggravated by the fact that usually workers stopped along the way to talk. To better understand the impact of excessive motion, the different movements mentioned are represented in Figure 24.

Figure 24 - Visual representation of the main movements done

Also, the different movements were analysed to understand which are most frequent. As it was perceptible in Figure 23, most of motion seemed to originate in building 2, which was confirmed by an analysis of the origin of movements (Figure 25).

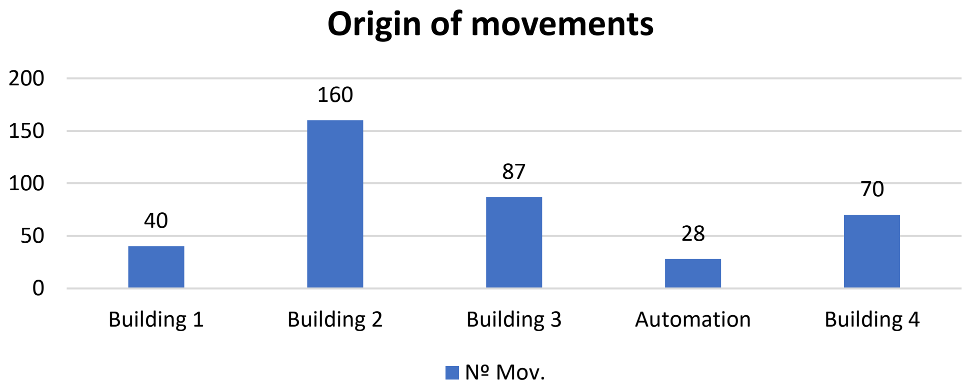

Figure 25 - Origin of registered movements

After the analysis of the data, some conclusions were withdrawal:

- The daily motion is, indeed, excessive;
- Building 2 is the origin of a great number of movements, having the higher significance;
- Most of movements to warehouse are done by workers from building 2, followed by workers from building 4;
- Most of movements to the bathroom are done by workers from building 3;
- Building 3, building 1 and WC represent 66.67% of the destination of movements from building 2;
- Despite representing the second major origin of movements, 57.14% of movements from workers on building 3 are to the bar and WC.

The main questions arising from these conclusions are:

i. Why the number of movements originating in building 2 is so high?

ii. Why there is such a great number of workers from building 2 going to the warehouse?

iii. What other causes originate the excessive motion?

Non-value-added activities

The goal for any process is to have the maximum of Value-Added activities (VA), as they represent what the customer is willing to pay for; Non-Value added (NVA) activities represent a negative impact on costs and are to be eliminated – still, the existence of this type of activities means that there is room for improvement. Another type of activities considered, the Business Value Added activities (BVA) are those that add no value to the product or process but need to be done to keep things flowing.

Sometimes it's not easy to distinguish these types of activities; in this analysis, activities like talking, getting tools, etc, were considered NVA, and activities like cleaning the workstation or make registrations on software were classified as BVA.

To quantify this, daily walks through all workstations were done, randomly, to observe what workers were doing and register it. Instead of measuring times, were registered occurrences (for example, "Assembling" or "Drinking Water").

With the collected data was possible to calculate the frequency of each type of activities, characterizing the state of the process (Figure 26) and the state of each section (Figure 27).

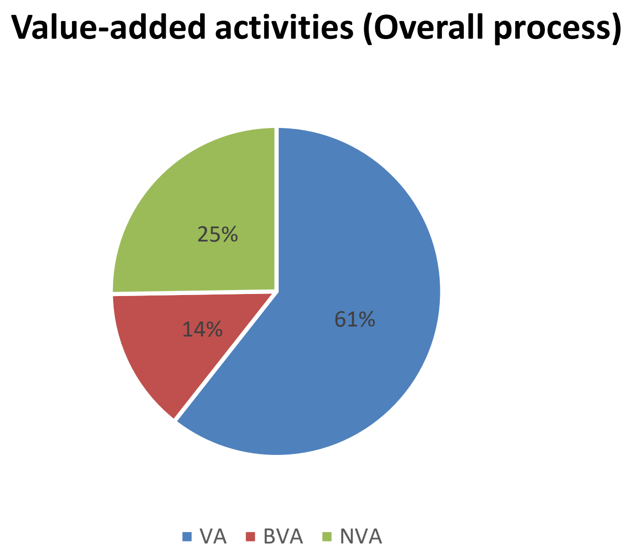

Figure 26 - Quantification of types of activities of the overall process

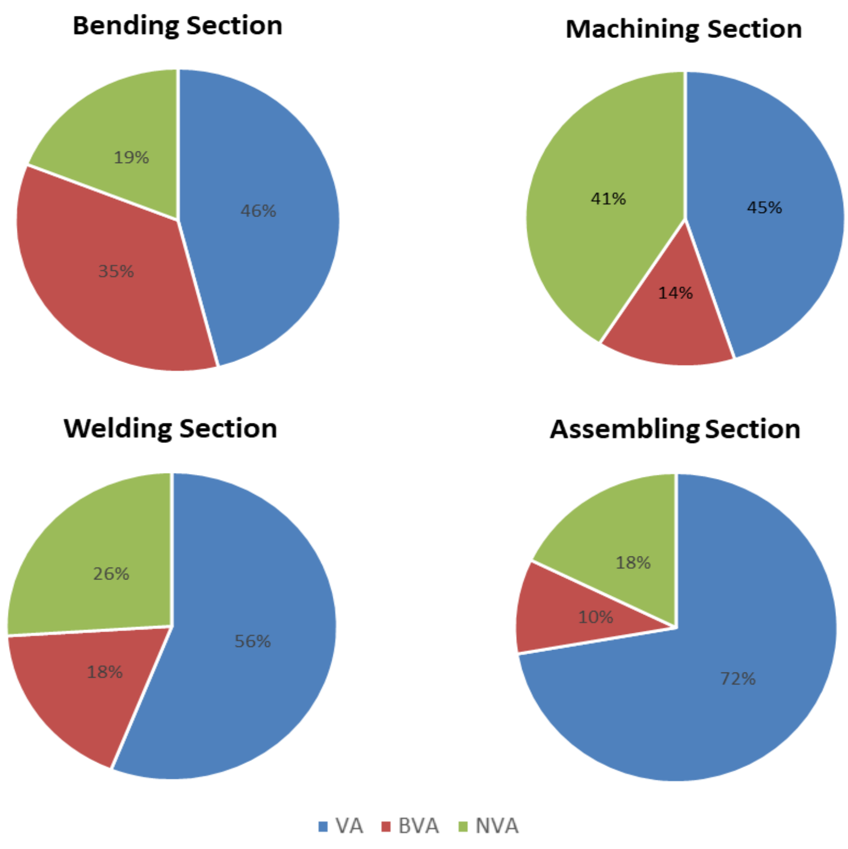

Figure 27 - Quantification of types of activities by section

This analysis revealed a not so good performance, as only 61% of activities add value to the process, versus 25% of non-value-added activities. It was also possible to conclude that machining was the section with the lowest productivity, with a concerning number of 41% of NVA activities.

Giving the results, it was mandatory to understand which type of NVA activities had the major impact in the poor performance of the process. The activities were quantified in a Pareto chart (Figure 28).

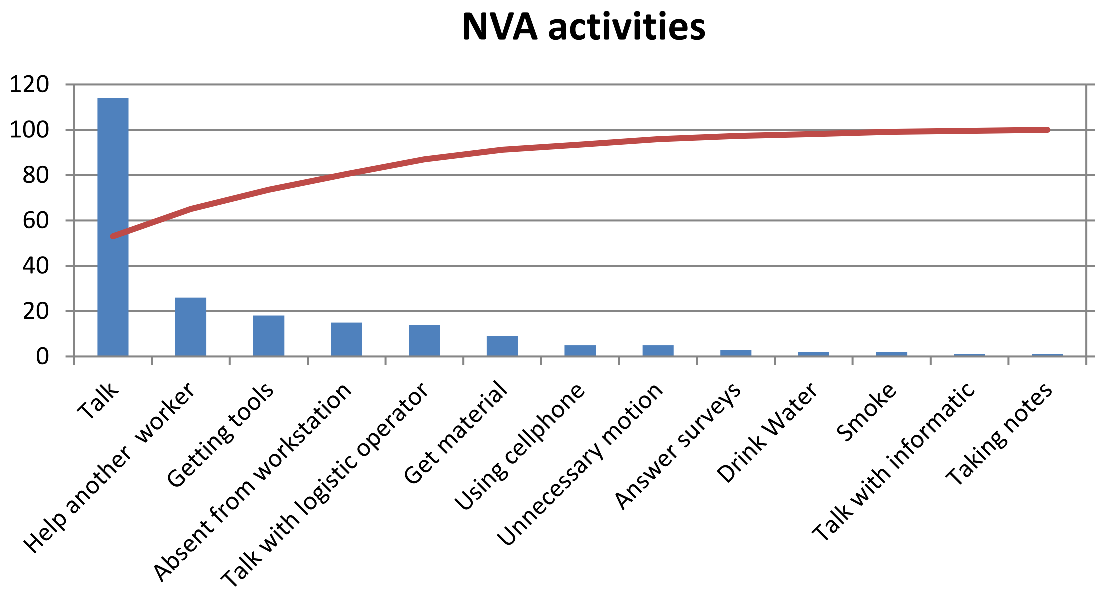

Figure 28 - Pareto chart of NVA activities

As expected, talking has a high significance when it comes to NVA activities; this requires further analysis to understand the reasons, as many of them may be related with the process (insufficient information, lack of work to do, etc.).

BVA activities cannot be eliminated, but very often there’s room for improvements. For this reason, another Pareto chart was done, this time regarding BVA activities (Figure 29).

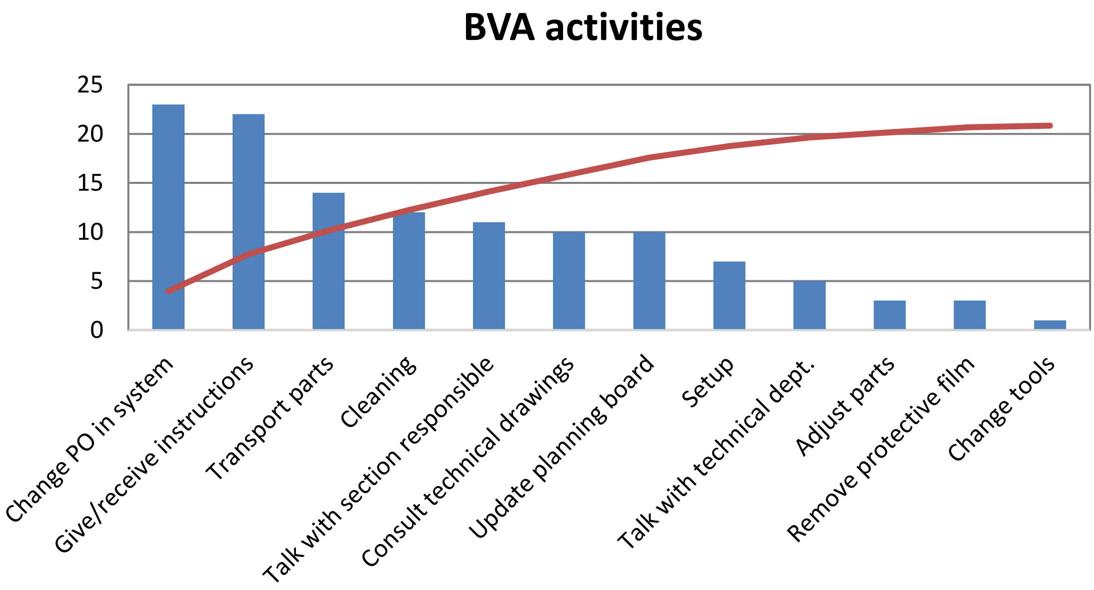

Figure 29 - Pareto chart of BVA activities

In this case, there’s not an activity that stands out, but registrations in the system, need of instructions, transport parts, cleaning and talking with the section’s responsible represent about 80% of BVA activities.

The main conclusions are:

- Currently the process shows a poor performance, with only 61% of activities adding value;
- Machining sections has the poorest performance, with only 45% of VA activities;
- Bending section presents the highest percentage of BVA activities;
- Talk, help another worker and getting tools are the main NVA activities;
- Making registrations in the systems and give or receive instructions are the main BVA activities.

Giving this, the main questions to be answered are:

iv. Why does machining section presents such a poor performance?

v. Which BVA activities are affecting the bending section and why?

vi. Why the NVA activities with higher impact occur?

Main causes of waste

After characterizing the waste in the process, it was necessary to comprehend why it occurs; getting to its causes was done by answering the previous questions, for which the inputs of section's responsible and workers were crucial.

For questions i), ii) and iii) the main reasons were:

- Building 2, due to changes occurring in production's management, is currently without a responsible, being the responsible for building 3 temporarily assuming this role and consequently, being overloaded; as there's no way, in this building, to sign when help is needed, workers often go search for the responsible;
- There's also no way to warn the logistic operator if some material or tools are missing, so workers try to locate him or go directly to the warehouse to get what they need;
- Sometimes the material for a PO prevenient from cut is transferred to bending when most of the parts, instead of all, are cut. The worker in bending then goes to building 1 to ask for the missing parts, instead of starting work on the material that already is on the workstation;
- There was only one battery drilling machine, located in building 3, so workers from building 2 need to get it and then return it;
- There is no specific place for pallet holders which, combined with the lack of discipline, implies that workers spent a lot of time searching for one, often finding several "abandoned" on the same place;
- There's only one computer in machining section to change the register of PO or consulting technical drawings; with usually 5 or 6 workers doing more than one PO daily, having to wait to use the computer is frequent. There's also just one computer for welding section and one of the bending machines. This situation creates a lot of motion.

As for questions iv), v) and vi):

- Machining section is in building 2, that has the highest quantity of motion, so it is expectable that its performance is not so good;

- As the workstations in turning and drilling sections have a cell layout, often with one worker for each machine, workers are often seen talking, affecting their productivity;
- Due to the nature of fabrication work, there's a great need for replacing tools – as the tools are stored in the electronical warehouse, sometimes workers must wait more than one hour to replace the tool needed to continue the job;
- Setups and changing tools are frequent in bending;
- The need to check technical drawings in bending is constant; as they are archived in paper format, workers spend some time looking for the one they need;
- As the technical drawings sometimes are not correct or the instructions are not clear, there's the need to check with the responsible how to do things (this is common to all fabrication);
- Contrary to assembly, fabrication is not organized according to the 5S's philosophy: there are tools not needed, needed tools are lacking and the workspace is not very organized;
- Heavy products or with high dimensions need an extra work to help wrapping after the assembly, since there are no efficient tools to do it;
- There is not a logistic daily route implemented to check lack of materials and tools, so it's common to have to call the logistic operator.

4.4 Synthesis

The variability study was conducted with the objective to quantify it and identify its root causes, by analyzing the production process. Through the quantification of waste was possible to understand that many of the causes found were also affecting variability. Several problems, in both analysis, were identified and since all of them contribute, directly or indirectly, to the existence of variability, all needed to be addressed.

A detailed analysis revealed that the main causes of variability are linked with lack of materials, lack of proper tools, inefficient steps of processes and material and information flow problems.

Though, even with the main causes identified, it was not possible to quantify the process variability, since the production times obtained through the informatic system, as found during the study, are not reliable.

As for waste, it was possible to identify excessive motion and a poor performance of the overall process (only 61% of VA activities), related mainly with the lack of proper tools and work conditions, inexistence of a logistic route to check needs, missing or wrong technical information, scarce supervision, and lack of discipline.

The improvement plan defined to address the problems identified is presented on chapter 5.

5 Improvement actions

Once the process was measured and several problems were identified, improvement actions needed to be implemented. This was done based on the Improve and Control phase of the DMAIC methodology, to define a structured plan of actions, with the objective of not only to improve the process, but also to integrate the improvements in the daily routine of production.

This section presents the plan of improvements to be implemented and how it was conceived, also giving an insight look on implementation challenges.

5.1 Problems approached

As mentioned in section 4.4, many variability and waste causes were identified during the process analysis. Since it is not reasonable to approach all the problems at once, the first step was to group the occurrences regarding variability according to their nature. After this, the data collected about the major wastes were also grouped, as many of them also regarded variability. This resulted in twelve distinct situations to be improved, represented on Table 5.

Table 5 - Problems approached on the definition of the improvement plan

ID[4]	Problem
1	Workers go to other workstations to change the registration of the PO in course and to consult technical drawings
2	Workers go to other workstations to get tools
3	Workers leave their workstations to help other workers
4	High number of non-conform parts or without all the processing
5	High number of workers talking
6	Assembled products wait long time for inspection
7	Incorrect registrations of production times on the system
8	Excess of motion
9	Inexistent or not followed Standard Work
10	Great deviations of production times relatively to the BOM and between workers
11	Lack of parts in the supermarket
12	Lack of material during operations

5.2 Improvement plan

With the problems to approach defined, brainstorm sessions were done with all the sections' responsible. Being the people with more knowledge about all the operations and the major problems, their insight was essential to validate some actions proposed, to propose other improvements and to choose the best way to approach each problem. After adjusting the plan

[4] The ID attributed to each problem has no relation with its magnitude, meaning that the problems presented are not ranked according to their impact.

and with a final validation of the people involved, some actions were defined to each problem, as well as a responsible for each action.

There was then the need to prioritize the actions. This was done by classifying each one according to four parameters: time of execution, difficulty, investment needed and impact on the problem, obtaining a total by summing all the classifications. As not all the parameters had the same weight when prioritizing the actions, a weighted total (WT) was calculated, accordingly to equation 5.1.

$$WT = 0.25 \times Difficulty + 0.25 \times Execution + 0.15 \times Investment + 0.35 \times Impact \quad (5.1)$$

Appendix G presents the prioritization of actions accordingly to equation 5.1.

Actions with a short and easy execution were classified as "Immediate", this is, to be started immediately after the plan definition. Next, as actions with different responsible could be executed in parallel, for each responsible the prioritization was done according to the weighted total calculated of each action (unless the action could only be executed after the conclusion of another one). An example of this process is given on Table 6.

Table 6 - Example of the prioritization of actions for each responsible

ID	Weighted Total	Prioritization	Responsible
8.7	3,45	1	J
8.4	3,45	2	J
12.3	3,2	3	J
3.2	2,05	4	J
12.2	3,45	Immediate	J
11.3	2,7	1	D
11.2	2,7	2	D
7.5	2,65	2	D
11.1	1,85	3	D
7.4	3	Immediate	D

Once the actions were prioritized, conclusion dates were defined based on an estimation of the time needed for each action, as well as the steps to achieve the major action (appendix H) and represented on a Gantt diagram.

At the end of this study only small actions were implemented, namely the ones with an easy and quick implementation.

One example is the change of the light color code of the assembling stands. The previous color code was not efficient, as the yellow light signalized many different situations. Frequently the logistic operator moved to the workstation unnecessarily, because the worker needed the assistance of the responsible, and vice-versa. To avoid these situations, a new code was implemented (Figure 30).

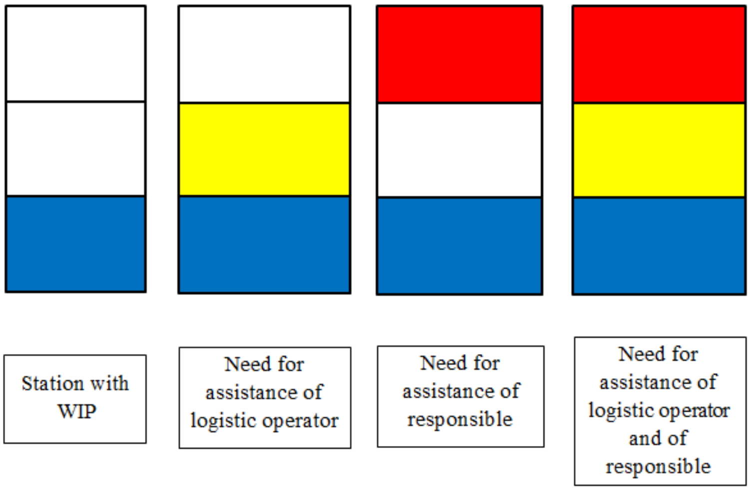

Figure 30 - New light color code implemented

This was a simple measure with reported improvements: workers mentioned that it was easier to signal their needs and the logistic operator said that his job was simplified, as he knows specifically when it's his help that is needed; the responsible of the assembling section also mentioned that like this it was faster to assist workers, as he knows when his is needed (contrasting with before, when the logistic operator went to the assembling stand and then look for him to tell him his help was needed).

5.3 Implementation Challenges

Despite all the potential of continuous improvement methodologies, many are the cases where the implementation of these philosophies failed. This unsuccess is essentially due to the inexistence of change management: improvements mean change, and change means uncertainty, and it is in our human nature to try to avoid the unknown.

According to Schantz (2018) some tips for successful implement change management are:

- **Follow a process.** Finding a process that is believed to work for the organization, considering the roles of leaders, managers, and individual contributors.
- **Start with the executives.** If there's no alignment and conviction at executive level, employees will know, and change won't be successful – usually executive team isn't personally impacted by change, but workers are.
- **Consider the needs and perceptions of all stakeholders in the change process.** The perspectives of employees, customers and partners should be considered.
- **Pay attention to the individual change process.** This involves 3 phases:
    1. *Letting go:* leave behind the way things were
    2. *Exploration:* confusion time between the old and new
    3. *Acceptance:* people start to let go of the past and explore the future
- **Focus on managers.** Managers are critical to the success, keeping employees engaged and productive.

As these are some fundamental steps to implement improvements, since the beginning of this study it was perceivable that implementation would be hard. There was a general disbelief from workers in top management and administration on matters like the willing to change and provide what is needed. Several years of pointing the same problems and nothing being done lead to a behavior of not caring anymore and do only what is expected, not providing improvement suggestions (in fact, there were several boxes for improvement suggestions on the shop floor, all of them empty; when asked about this, a worker replied, “We make suggestions, and everything remains the same, so I gave up”).

Also essential is to inform people clearly of the objectives of the project and why things are happening that way, avoiding misinterpretations and incorrect assumptions. This important step was skipped, so workers could only see people measuring times and doing registrations which raised suspicions and led to a defensive posture. The best example of the workers not knowing the goals and what was to be accomplished was the constant commentary “you are starting to build the house by the rooftop”, not understanding that small things being done were part of a whole.

Managers have a vital role on facilitating change and this was the first obstacle. Individuals and their needs are important in the development of a plan, and the management team was constituted by very different people:

- Person 1 (P1): the person who feels that is essential to the good performance of the company; wants everyone to do everything right at the first time and has a bossy behavior towards others;
- Person 2 (P2): the person who wants to change everything and feels capable of doing everything, saying yes to anything, accepting responsibilities immediately without even reflecting if it is accomplishable;
- Person 3 (P3): the person who takes everything personally, likes to feel in charge and be recognized, often having a behavior considered rude by subordinates, but in reality, is very helpful and cares about others
- Person 4 (P4): the person who is very quiet and lives on his own world, apparently leading with problems in a relaxed way; seems to always be listening, but dismisses everything that interferes with own work or represents extra work
- Person 5 (P5): the person who behaves like the owner of the section, feeling that has nothing to do with the rest and grabs about having everything organized and under control

The first resistance to change was clearly during brainstorming sessions. To start, P1 was left out of meetings due to decision of the production director – this wasn’t welcomed by others, as they felt that such an important person should be there. When data were presented, reactions were completely different: while P2 looked at data as an opportunity to make some changes, P5 behaved like all that didn’t apply to his section and P4 acted neutrally, making small suggestions, and agreeing with everything; on the other hand, P3 felt it like a personal attack and adopted a defensive posture, taking a lot of extra time to be convinced that those actions could in fact improve results.

After the plan was defined, these people had the role to act like leaders and engage workers. However, P5 rapidly did all actions under his responsibility, saying that “his job was done”; P4 simply said that “had more important things to do”; P1, who despite not being present, was included in some improvements, acted like not knowing and had nothing to do with that; P2, as expected, volunteered to be responsible for a lot of actions, but did almost nothing – when mentioned the subject, the answer was always “I know, I know, I haven’t forgot”. Surprisingly, the only proactive was P3, starting immediately to implement actions and make an effort to meet the deadlines defined; being the more resistant to change person at first, was the one more committed to make changes at the end.

This attitude was noticed by workers, aggravating the feeling of disbelief. However, some intervention sessions were done with workers, to present the data and what was expected with the improvement plan. Again, most workers interpreted that as an attack, starting to make justifications and find guilts; by the end of the session, some were giving a lot of suggestions to improve their work. Though, on the following days, there was an uncomfortable and tense work environment, with some workers teasing the ones of the sections with biggest NVA activities and doing jokes like "someday day we'll be chained to workstations".

Concluding, the message was not understood, and all the factors mentioned didn't allow the implementation of significant actions by the end of this study. Even small actions like identify a place for pallet holders didn't start the right way, as the problem persists, mainly due to lack of discipline. Another crucial factor was the inexistent sense of urgency, mainly due to the good market performance of the company.

5.4 Synthesis

This chapter presented the definition of actions to reduce variability and waste identified.

The problems considered to have the biggest impact were approached by a set of actions, designed with the help of section's responsible. Measures were prioritized, and deadlines specified.

When starting to implement actions, the resistance to change was evident, not only by workers, but also by managers. Disbelief in administration, unclear message of what was to be done and why and inexistent sense of urgency were the main obstacle for improvements.

To make this kind of projects work, it is essential to properly manage change, ensuring that improvements done are sustained in long term.

6 Conclusions and future work

This study was developed in the scope of a project of continuous improvement, with the goal to improve processes by reducing variability. Other objectives were set, aiming to identify variability causes, quantify waste and its contribution to variability, projecting tools to quantify and control variability in the future. The focus was a better definition of lead-times and improving performance, as part as the strategic growth of the company.

Production processes were followed and analyzed, as well as the flows of material and information, to quantify variability and get to its root causes. During this analysis, other problems not directly linked to variability were identified, being also analyzed. After, brainstorming sessions were done to find solutions to the problems causing the greatest impact on performance – some were quick hits, while others required more time and effort. An improvement plan was done, based on the existent problems.

While on the improving phase, the greatest "enemy" of continuous improvement was revealed: resistance to change. With change not being properly addressed at the beginning and with a climate in nothing favorable to it, the implementation of actions was of extreme difficulty, even in the case of simple actions. By the end of this study, almost no actions were done, being impossible to measure the impact of the improvement plan on the process.

6.1 Main conclusions

Demand variability was quantified and concluded to be unpredictable, having a great impact on production planning and interfering with the goal of stock reduction.

Regarding the process, it was possible to conclude that it was not under control and there was significant variability affecting it. As expected, this was more evident on the assembly process, since being the downstream process concentrates the variability of all processes. Another cause of variability in assembly is the type of products: high complexity and lots of parts to assemble make this process vulnerable to variability.

As for lead-time variability, the root causes identified were related to lack of materials (mainly due to problems in materials flow), lack of proper tools and means to work with large and heavy products, operations unperformed and quality problems, often leading to rework.

The registration system also revealed to be a cause of variability, as the system is slow and inefficient and almost always leads to registration errors. In fact, it was found that data presented on the system regarding production times is not reliable, making impossible to have a correct definition of lead-times or perform statistical analysis to assess the process control and capability.

The analysis of the process also revealed an excess of NVA activities, as only 60% of activities were adding value. This poor performance was highly linked to the excess of motion verified. It was possible to conclude that the sections with higher NVA activities were in the building with the greatest number of unnecessary motion. Also, not being a source of variability on the assembly process, due to the functioning of this section, motion is a major contributor for variability in upstream processes.

The contrast found between the performance of assembly and fabrication sections is partially justified by the investment done on assembly: workstations organized according to the 5S's philosophy and ways to signal needs; on the other hand, fabrication section is poorly organized, workers don't have the necessary tools or way to signal needs of material or assistance, leading to movements to warehouse to solve the problem on their own.

6.2 Future work

With several problems identified throughout the entire process, an improvement plan had to be defined, to provide the best work conditions possible and reduce variability, therefore improving the production process.

Nevertheless, the natural resistance to change, associated with a disbelief in the administration's willing to change and the status quo were great obstacles for improvements. As change was not properly managed, it takes longer for people to accept changes and see them as an improvement, which had a big impact on the results of this study.

Despite process improvement being the main goal, it was not possible, during the time of this study, to implement the actions defined and measure their impact on the process. However, other problems identified, if acted upon, can lead to significant process improvements, perhaps bigger than a reduction of variability.

The defined improvement plan appears to be capable of providing good results if correctly implemented. It's necessary to implement the actions delineated and keep the deadlines defined, as this is essential to keep the project going and break the status quo. With the capability of the improvement plan to assure improvements in short term, addressing the problem of resistance to change should be a goal of the administration to guarantee that those short-term improvements become part of the process.

Implementing the 5S's philosophy on fabrication area is an essential action to a better performance, as the majority of NVA activities in this area is related to lack of tools and materials and an inefficient workspace organization.

The inefficiency of the current system of registration was evident during this study. An implementation of a system that allows workers to register production times easier and with less time, with the possibility to register times of activities like cleaning, would allow the company to obtain the correct production times and lead-time definitions, as well as measure times of Business Value Added activities. This is of great important to easily assess the state of the process in terms of value added and identify possible improvements. Correct registrations would also allow a statistical analysis of the process, evaluating its capability and variability.

In general, the questions delineated for this study were answered, as variability causes were identified as well as several improvement opportunities, even though process improvements were not implemented and evaluated. Though resistance to change was not quantified, its effects, together with the current environment of the company due to the change of the production director, had a major impact on the results obtained.

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APPENDIX A: Internship Chronogram

Table 7 - Internship Chronogram

Semana	Foco	Entregável do período
W38 (2 dias)	Integração: - Tecnologia & Inovação (+) - Sistemas de Informação (+) (+) - Áreas de maior foco	
W38 (restant e sem.)	Produção & Operações: - Corte / Fabrico / Assemblagem / Armazém - Perceber operação, tarefas e fluxos;	Fluxograma produtivo da para Produtos Standard.
W39 (1 dia)	Produção & Operações: - Projetos Especiais - Perceber operação, tarefas e fluxos	Fluxograma produtivo da para Projetos Especiais.
W39 (restant e sem.)	Conhecer e aprofundar as ferramentas informáticas utilizadas na Produção & Operações - Projetos; - Ordens de Fabrico; - Gamas Operatórias Estudar a lógica e o funcionamento de cada um destes dossiers. Como são criados, qual o seu propósito, como são geridos.	Mapa de representação dos vários dossiers, que represente as seguintes dimensões: - Owners dos dossiers; - Interligação dos dossiers; - Papel e Outputs dos dossiers;
W40	Análise ABC dos produtos finais standard para o período de 1 ano. - Classificação dos produtos; - Variabilidade da procura; - Índice de frequência de encomendas; Definir metodologia para análise de variabilidade e conjunto de produtos alvo - criar ferramentas eventualmente necessárias para o registo de informação (Abordagem baseada no DMAIC - SixSigma)	Análise ABC, com conclusões em cada uma das dimensões; - Identificação de 1 artigo por família de produtos para análise e acompanhamento de produção; Ferramentas de monitorização e análise de variabilidade (Abordagem DMAIC - SixSigma) Ação de formação P&O + T&I - Abordagem DMAIC
W41 a W45	Acompanhamento de referências identificadas: Análise final da variabilidade, quantificando e identificado as suas causas e efeitos. Identificação de possíveis medidas a implementar para corrigir variabilidade. Estruturação do plano de atividades e cronograma para as melhorias a implementar.	No final de cada semana: Relatório de acompanhamento das referências com: - Análise do que foi feito; - Estruturação de dados; - Análise de desvios; - Conclusões; - Plano de ação para a semana seguinte.
W46	Consolidação e análise aprofundada da informação retirada da análise a cada uma das referências, com identificação e quantificação de desvios, causas e efeitos. Finalização do plano de ação de medidas corretivas para os desvios e respetivas causas identificadas	Relatório final do estudo de variabilidade Plano de ações c/ cronograma de implementação.
W47 a W50	Implementação do plano de ações.	Relatório de implementação de medidas e análise à sua eficácia.
W51 a W01	Acompanhamento e análise final da eficácia das ações implementadas e do plano em geral. Construção de ferramenta de análise de variabilidade a ser implementada de forma definitiva na gestão da produção.	Relatório de eficácia das ações implementadas. Ferramenta de análise de variabilidade.
W02	Elaboração do relatório de dissertação	N/A

APPENDIX B: The 7 wastes of Lean

Table 8 - Lean 7 wastes: description and examples (source:(Melton 2005))

Type of waste	Description	Within the process industry	Example symptom
1. Over production	• Product made for no specific customer • Development of a product, a process or a manufacturing facility for no additional value	• Large campaign—large batch and continuous large-scale manufacturing processes • Development of alternative process routes which are not used or the development of processes which do not support the bottleneck • Redesign of parts of the manufacturing facility which are 'standard', e.g., reactors	• The extent of warehouse space needed and used • Development and production organization imbalance • An ever changing process (tweaked) • Large engineering costs/time associated with facility modifications
2. Waiting	• As people, equipment or product waits to be processed it is not adding any value to the customer	• Storage tanks acting as product buffers in the manufacturing process—waiting to be processed by the next step • Intermediate product which cannot leave site until lab tests and paperwork are complete	• The large amount of 'work in progress' held up in the manufacturing process—often seen on the balance sheet and as 'piles of inventory' around the site
3. Transport	• Moving the product to several locations • Whilst the product is in motion it is not being processed and therefore not adding value to the customer	• Raw materials are made in several locations and transported to one site where a bulk intermediate is made. This is then transported to another site for final product processing • Packaging for customer use may be at a separate site	• Movement of pallets of intermediate product around a site or between sites • Large warehousing and continual movement of intermediate material on and off site rather than final product
4. Inventory	• Storage of products, intermediates, raw materials, and so on, all costs money	• Economically large batches of raw material are purchased for large campaigns and sit in the warehouse for extended periods • Queued batches of intermediate material may require specific warehousing or segregation especially if the lab analysis is yet to be completed or confirmed	• Large buffer stocks within a manufacturing facility and also large warehousing on the site; financially seen as a huge use of working capital
5. Over processing	• When a particular process step does not add value to the product	• A cautious approach to the design of unit operations can extend processing times and can include steps, such as hold or testing, which add no value • The duplication of any steps related to the supply chain process, e.g., sampling, checking	• The reaction stage is typically complete within minutes yet we continue to process for hours or days • We have in process controls which never show a failure • The delay of documents to accompany finished product
6. Motion	• The excessive movement of the people who operate the manufacturing facility is wasteful. Whilst they are in motion they cannot support the processing of the product • Excessive movement of data, decisions and information	• People transporting samples or documentation • People required to move work in progress to and from the warehouse • People required to meet with other people to confirm key decisions in the supply chain process • People entering key data into MRP systems	• Large teams of operators moving to and from the manufacturing unit but less activity actually within the unit • Data entry being seen as a problem within MRP systems
7. Defects	• Errors during the process—either requiring re-work or additional work	• Material out of specification; batch documentation incomplete • Data and data entry errors • General miscommunication	• Missed or late orders • Excessive overtime • Increased operating costs

APPENDIX C: Special Projects VSM

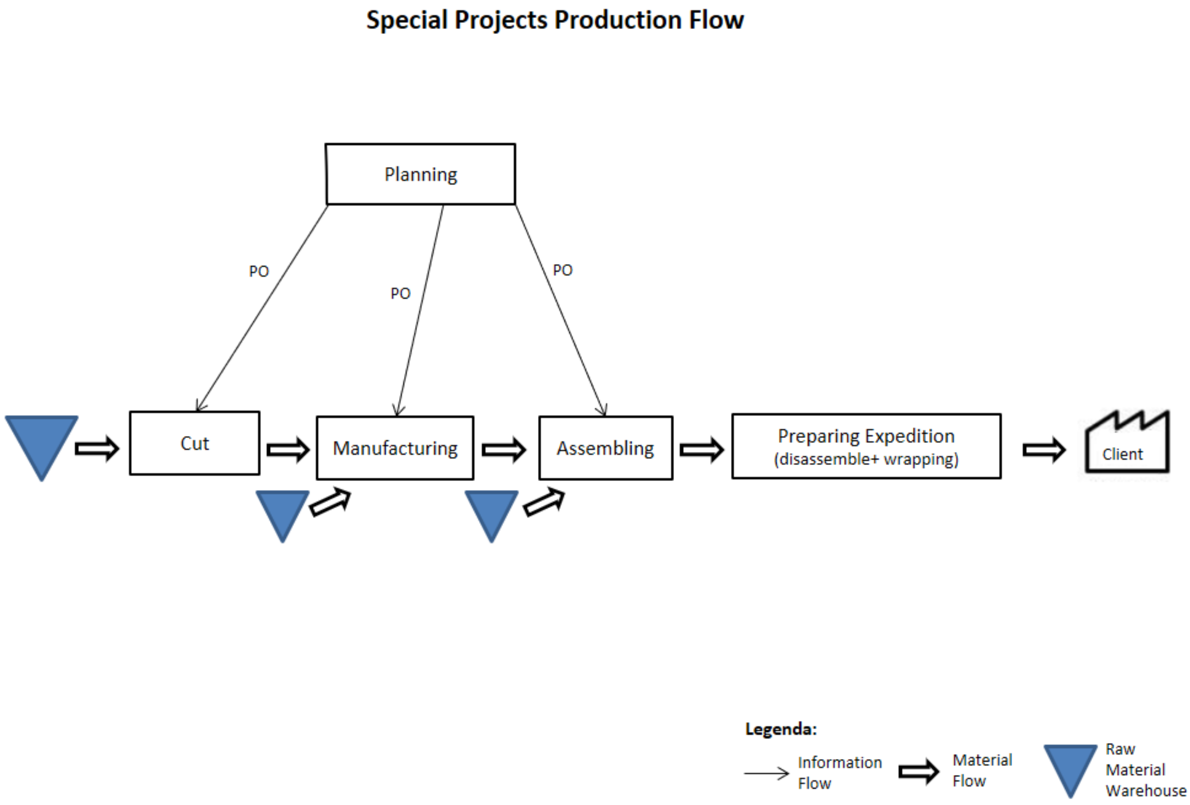

Figure 31 - VSM of Special Projects production flow

APPENDIX D: Example of a Bill of Materials of a product

Operation/Article	Time	Quantity
Ref. X	100min	
Operation A	50min	
Art. 1		3
Art. 2		2
Operation B	10min	
Art. 2.1		1
Art. 2.2		1
Operation C	5min	
Art. 2.1		1
Operation D	15min	
Art. 3		4
Art. 4		3
Art. 5		3
Operation C		
Art. 5.1		2
Operation B	10min	
Art. 6		8
Art. 7		8
Art. 8		4
Art. 9		5
Operation E	5min	
Operation F	5min	

Figure 32 -Example of a BOM

APPENDIX E: ABC/XYZ Analysis

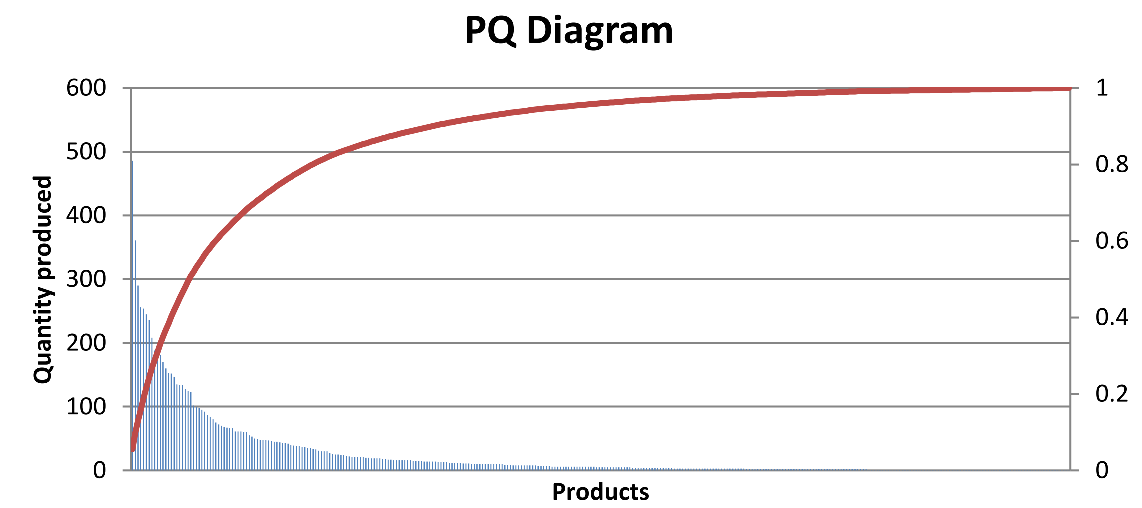

Figure 33 - Pareto chart of ABC analysis (quantities)

Table 9 - Summary of ABC/XYZ analysis (quantities)

	X	Y	Z	%
A	0	0	68	20%
B	0	0	86	25%
C	0	0	185	55%
%	0%	0%	100%	100%

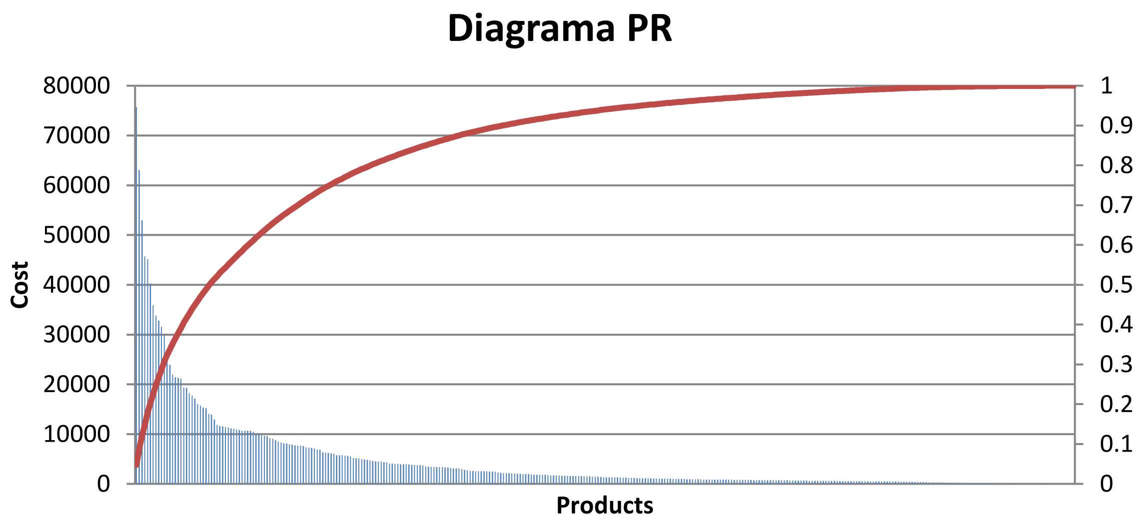

Figure 34 - Pareto chart of ABC analysis (cost)

Table 10 - Summary of ABC/XYZ analysis (cost)

	X	Y	Z	%
A	0	0	88	26%
B	0	0	94	28%
C	0	0	157	46%
%	0%	0%	100%	100%

APPENDIX F: Registration of production times

Table 11 - Registration of production times measured

PO	Ref.	Family	Worker	Predicted Qt.	Produced Qt.	Estimated Production Time (unit)	Production Time (unit)	System Registration (unit)	Deviation (estimated vs. observed)	Deviation (system vs. observed)
37215	A	Conveyor	R	3	3	25	31,67	22,67	27%	-28%
37297	A	Conveyor	R	6	3	25	30	22,67	20%	-24%
37482	A	Conveyor	V	3	3	25	17	22,67	-32%	33%
36844	A	Conveyor	V	1	1	25	14	23,00	-44%	64%
37355	A	Conveyor	V	8	8	25	11,375	22,75	-55%	100%
38524	A	Conveyor	L	6	6	25	13,33	22,67	-47%	70%
38605	A	Conveyor	L	5	5	25	17,6	22,80	-30%	30%
35782	G	Conveyor	R	20	13	20	25,85	23,30	29%	30%
36877	H	Wheel Curves	L	7	7	90	61,14	84,71	-32%	-80%
35822	D	Adjustable conveyor link	R	15	10	20	28	18	40%	-94%
35822	D	Adjustable conveyor link	R	15	3	20	18,6	18	-7%	-81%
35788	I	Adjustable conveyor link	R	10	2	10	18,6	8	86%	-91%

APPENDIX G: Prioritization of improvement actions

Table 12 - Classification of execution, difficulty, investment and impact of improvement actions

Classifications			
Execution	**Difficulty**	**Investment**	**Impact**
1 - Slow (+ 2 months)	**1** - High	**1** - High (>500€)	**1** - Very Low
2 - Medium (2 weeks to 2 months)	**2** - Medium	**2** - Medium (100€-500€)	**2** - Low
3 - Fast (max. 2 weeks)	**3** - Low	**3** - Low (<100€)	**3** - Medium
			4 - High
			5 - Great

Table 13 – Example of prioritization of improvement actions

ID	Action	Execution	Difficulty	Investment	Impact	Total	Weighted Total	Prioritization	Precedences
1.1	Acquire an informatic device (computer/industrial tablet) for each workstation	2	3	1	5	11	3,15	1	-
2.1	Readjusting tools on assembly stands	2	3	2	5	12	3,3	1	-
3.1	Create supports to and ways to move large pieces	3	3	3	4	13	3,35	Immediate	-
3.2	Change the way to wrap heavy products, so they can be wrapped by just one person	1	1	1	4	7	2,05	4	-
3.3	Workers should only be helped by the responsible or logistic operator	3	3	3	3	12	3	Immediate	-
3.4	Acquire lifting platforms	2	3	1	4		2,8	1	-
4.1	Implement quality system by processes	1	1	3	5	10	2,7	2	-
4.2	Buy better raw material (steel sheet)	1	2	1	4	8	2,3	7	-
4.3	Create workstation to threading and countersink	3	3	3	4	13	3,35	Immediate	-
5.1	Make people aware about excessive talking	3	3	3	2	11	2,65	Immediate	-
5.2	Provide all the work instructions needed for each workstation	1	1	3	4	9	2,35	5	-
5.3	Change layout of machining area	2	2	3	3	10	2,5	3	-
5.4	Make workstations more visible	2	2	2	3	9	2,35	6	5.3
6.1	Assign inspection task to more than one person	2	2	3	4	11	2,85	3	-
6.2	Create area next to assembly stands to place products waiting for inspection	3	3	3	3	12	3	Immediate	-
6.3	Define new light colours code	3	3	3	3	12	3	Immediate	
7.1	Correct software problems	1	1	3	2	7	1,65	12	-
7.2	Implement a more efficient system to register PO times	1	1	1	5	8	2,4	4	-
7.3	Create automatism to stop PO in course when doing another task	1	1	1	5	8	2,4	4	7.2
7.4	Recreate codes for intern orders (cleaning, transporting, etc)	3	3	3	3	12	3	Immediate	-
7.5	Keep internal PO in visible places and in each workstation	3	3	3	2	11	2,65	2	7.4
7.6	Make people aware about the need to make correct registrations	3	3	3	2	11	2,65	Immediate	-
8.1	Make people aware not to leave workstations	3	3	3	2	11	2,65	Immediate	-
8.2	Implement light system on pavilion 2	2	2	1	5	10	2,9	2	-

APPENDIX H: Improvement plan defined

Table 14 - Improvement plan defined

ID	Action	Responsible	Priority	Conclusion Date
1.1	Acquire an informatic device (computer/industrial tablet) for each workstation	A	1	09/03/2018
2.1	Readjusting tools on assembly stands	P	1	02/02/2018
3.1	Create supports to and ways to move large pieces	P	Immediate	22/12/2017
3.2	Change the way to wrap heavy products, so they can be wrapped by just one person	J	4	15/06/2018
3.3	Workers should only be helped by the responsible or logistic operator	P	Immediate	22/12/2017
3.4	Acquire lifting platforms	A	1	19/01/2018
4.1	Implement quality system by processes	A	2	30/03/2018
4.2	Buy better raw material (steel sheet)	A	7	23/02/2018
4.3	Create workstation to threading and countersink	G	Immediate	12/01/2018
5.1	Make people aware about excessive talking	A	Immediate	22/12/2017
5.2	Provide all the work instructions needed for each workstation	A	5	31/05/2018
5.3	Change layout of machining area	A	3	30/03/2018
5.4	Make workstations more visible	A	6	11/05/2018
6.1	Assign inspection task to more than one person	P	3	09/03/2018
6.2	Create area next to assembly stands to place products waiting for inspection	P	Immediate	29/12/2018
6.3	Define new light colours code	P	Immediate	15/12/2017
7.1	Correct software problems	A	12	10/07/2018
7.2	Implement a more efficient system to register PO times	A	4	25/05/2018
7.3	Create automatism to stop PO in course when doing another task	A	4	25/05/2018
7.4	Recreate codes for intern orders (cleaning, transporting, etc)	D	Immediate	05/01/2018
7.5	Keep internal PO in visible places and in each workstation	D	2	29/12/2017
7.6	Make people aware about the need to make correct registrations	A	Immediate	22/12/2017
8.1	Make people aware not to leave workstations	A	Immediate	22/12/2017
8.2	Implement light system on pavilion 2	P	2	02/01/2018
8.3	Implement light system to signalize lack of material on pavilion 4	P	Immediate	12/01/2018
8.4	All needs of tools and materials must be communicated to the logistic operator	J	2	29/12/2017
8.5	Put some material on pallets to prevent scratching pieces	A	Immediate	29/12/2017
8.6	Buy 2 battery drilling machines for pavilion 2	A	Immediate	29/12/2017
8.7	Allocate Transport of parts between nave 1 and nave 2 to just one person	J	1	22/12/2017
8.8	Place a pallet transporter in each nave, on the respective place	J	Immediate	22/12/2017
9.1	Create, review, and implement Standard Work	A	10	10/07/2018
9.2	Form operators according SW	P	11	10/07/2018
10.1	Review BOMs	P	9	10/07/2018
10.2	Give proper formation to workers, specially to those who usually work on projects outside	A	8	30/03/2018
10.3	Create and signal properly area to PO interrupted	P	Immediate	12/01/2018
11.1	Simplify the emission of Kanban PO	D	3	10/07/2018
11.2	Revaluate the number of parts in the supermarket and make eventual modifications	D	2	31/05/2018
11.3	Improve planning to prevent interference from special projects on standard products production	D	1	31/05/2018
12.1	Improve coordination between shop department, production department and warehouse	A	2	31/05/2018
12.2	Define identification method to products arriving at the warehouse that are missing in PO released	J	Immediate	22/12/2017
12.3	Create daily logistic route	J	3	02/01/2018