Analysis of the manufacturing process of bushings in landing gear maintenance

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July 2019

Abstract

This work intends to analyze the manufacturing process of bushings in maintenance of aeronautical components, more concretely landing gears. The aircraft covered in this study are the Embraer E170, and E190. The need to analyze the bushings manufacturing of these two aircraft follows the recent industrialization of the train maintenance process, which took place in the summer of 2017. The process implemented was based on the existing inefficiencies with regard to the process used in the production of bushings for the Embraer ERJ145 aircraft train. Taking into account lean thinking, and a prospect of continuous improvement, the current limitations and sources of waste were identified. In addition, all the necessary tools for manufacturing were identified and elaborated, namely the work letters, the procedures to be carried out, and the quantities of material needed. The work was done with the aim of making the process as efficient as possible, and in turn contributing to the company’s competitiveness. Through its implementation, it is not only intended to reduce costs, but also to reduce dependence on external suppliers. This greater independence contributes to a faster response of the company to the needs of the customer, thus contributing to its satisfaction. In order to guarantee this independence, a supermarket of raw material will be created, with the exact quantities of material per landing gear, being controlled by means of kanban cards.

Keywords: Bushing, Lean, Landing gear, Continuous Improvement, Kanban cards

1. Introduction

This work results from the cooperation between Instituto Superior Técnico and OGMA-Aeronautical Industry of Portugal. In the course of this work, it was intended to analyze the manufacturing process of the necessary bushings during the overhaul process of the landing gears. The aircraft involved in this study belong to the Embraer E-Jets family, specifically the Embraer E170, and Embraer E190. And the maintenance of the trains must be carried out every 20,000 flight cycles.

Bushings are mechanical components, usually metallic, used to reduce friction and serve as a support and guide for rotating, sliding or oscillating parts of a mechanical assembly, allowing them to move with a minimum of friction [6]. When intermediating the contact, the bushings also allow to reduce the wear of the parts that constitute the mechanical assembly, and whose replacement during the overhauls would be more expensive than just replacing the bushings. Its production in the aeronautical sector can only be carried out by the company if it has the aircraft production organization certification, also known as EASA Part 21.

This certification, in the specific case of OGMA, authorizes it to produce simple parts and composite assemblies in metallic or composite material.

The need to carry out this analysis arises with the industrialization of the overhaul process in the summer of 2017. The company, when already manufacturing the bushings of the Embraer ERJ145 aircraft, and having verified the economic benefit of the domestic production to the detriment of the external acquisition, decided analyze the production process for the other Embraer aircraft. In addition, it was intended to optimize the production process in order to make it faster and more efficient, using the lean philosophy. This philosophy focuses its attention on customer satisfaction, seeking to identify the waste in the production process in order to eliminate them, and thus add value to the customer [8].

The work carried out therefore appears to be of the utmost importance, since in a global market in which companies compete with each other, it is important not only that the service provided is of a high quality, even more so in the aeronautical industry, but it is also crucial that time to perform
the overhaul is as short as possible.

Taking ICAO (International Civil Aviation Organization) data, an average annual growth of 4.6% in passenger air transport is expected to be achieved by 2032. One of the regions that will contribute most is South-West Central Asia. In this region, the category that shows the greatest growth is domestic flights, with an evolution of 10% annually [4]. Between 2012 and 2042, an increase in the influence of domestic flights on global passenger transport is expected. In 2042, these accounted for 42% of total traffic. An example of this is the fact that domestic flights in Southwest Asia and North America occupy the first two places on the routes with the highest traffic. In conclusion, with regard to the evolution of the passenger market, it can be said that developing countries, whose market share has grown from 24% to 40% in the last decade, will continue to play a key role in the growth of passenger transport. China will cross the US, taking first place. The third place that was occupied by the UK, will be replaced by India [3].

Aircraft manufacturers can be grouped according to the number of seats available on them. The largest manufacturers, Boeing and Airbus, are engaged in aircraft with more than 150 seats, while competitors, Embraer and Bombardier, produce aircraft with less than 150 seats. In the particular case of Embraer, its offer is divided into two segments. A first comprising aircraft capable of carrying between 37 and 50 passengers, and is called the family ERJ. The other segment, the E-Jets family, has four aircraft with transport capabilities between 70 and 130 passengers. Comparing the aircraft of Bombardier and those belonging to the Embraer E-Jets family, the latter have a greater variability in terms of seats, a wider range, and a higher maximum take-off weight (MTOW). The recent merger in the aviation sector led Airbus to acquire the C-Series project from Bombardier, which enabled the European manufacturer to compete with Embraer’s offer. In response to this move by Airbus, Boeing formalized the acquisition of Embraer’s commercial aviation business, which has a market share of 24%. With respect to the E-Jets family, its presence in the market translates into a total of 1439 aircraft delivered and 133 to be delivered. Each aircraft is designed to perform 80000 flight cycles, which presupposes a total of 4716 overhaul of the landing gear by the year 2048.

Since the 1970s there has been an increase in competition in the aviation transportation sector, which has resulted in a cost reduction per seat. This strategy, which involved the purchase of larger aircraft, meant that seats were sold at lower prices so that the aircraft did not operate empty, which resulted in a decrease in revenue for airlines [2]. In order to counteract the decline in revenue, companies must tailor their fleet to demand from the market. Thus, the choice of a suitable aircraft allows to reduce the number of seats dedicated to low cost tariffs, thus maximizing revenue. In a study by the MIT and PADS Research, it was possible to conclude that there would be a 30% increase in revenue used a 130-seat aircraft compared to 170.

In the last decade, with the increase in demand derived from greater purchasing power, the appearance of low-cost airlines was a natural process. With the increase in the supply of these companies, some of the primary markets became more competitive, facing these difficult to fill their aircraft, which in turn leads to decrease in revenues. While in the primary markets there is an excess of supply, in the secondary supply is scarce, this being justified by the low traffic density. In the Asian market, it can be seen that the markets with the lowest available daily flights have a lower number of competitors. Secondary markets are also more profitable, compared to primary ones [1]. These secondary markets make up the majority of the routes in the region, due to the reduced are only feasible with the use of smaller capacity aircraft. By using this type of aircraft, it is possible to make operation in these markets profitable and expected increase in purchasing power in the region, it will be possible to offer a higher frequency of flights, which contrasts with the current situation where there is less than one daily flight. Having characterized the market of the region whose growth will be most accentuated, we can conclude that the use of smaller aircraft, such as those belonging to the E-Jets family, will of airline operations. In this way, it will be expected that the demand for this type of aircraft is maintained, also allowing a continuation of the maintenance programs of these aircraft.

2. Background

In this section we intend to enumerate the different processes involved in the manufacture of bushings. Therefore, it is divided into four sub-sections: raw material machining, surface treatments, thermal treatments, and finally non-destructive tests (NDT).

2.1. Raw Material Machining

The machining of the raw material is carried out by machines that operate according to numerical control by computer (CNC). In this way it is possible to automate, and increase the production capacity, since the operations are controlled through commands in the G-Code programming language. In the case of turning, it is necessary to include in the instructions a set of coordinates, X and Z, which define the contour of the part. X is the di-
The selection of inserts must be made according to the following parameters: geometry, class, shape, size, tip radius, and position angle. The geometries for turning are divided into three basic types that are optimized for finishing operations, medium machining and roughing. The grade of the insert depends on the material to be machined, and the information on the materials included in each class is established by ISO 513. The shape of the insert depends on two factors: the tip angle and the number of cutting edges. The size is defined by the diameter of the largest circumference that can be inscribed in its interior, its value being determined as a function of the depth of cut and the length of cut. Tip radius is an important factor in turning operations as it influences surface finish, chip strength, and chip breaking. The position angle, KAPR, is the angle between the cutting edge and the feed direction. Angles positions allow you to attenuate the tendency of vibration, turn corners to 90 degrees, and decrease the shear strength. However, they are more susceptible to notched wear.

The turning operation requires the definition of a set of parameters, such as, the cutting speed, the speed of rotation of the lathe, feed rate, and the depth of cut. Among these variables, the life time of the insert is more influenced by the cutting speed [5]. The relationship between tool life, and the cutting speed, is translated by Taylor’s Law:

\[ V_c T^n = C, \]  

where \( n \) and \( C \) are constants, \( T \) is the lifetime of the tool in minutes, and \( V_c \) at the cutting speed in meters per minute. The value of \( n \) depends essentially on the material of the tool, and \( C \) on the material being machined and the cutting conditions used. The value of \( C \) corresponds to the cutting speed associated with a tool life of one minute. In order to determine the speed of rotation of the lathe, in revolutions per minute (RPM), the following expression is used:

\[ N = \frac{1000V_c}{\pi D}, \]  

where \( D \) represents the diameter of the rod.

### 2.2. Superficial Treatments

In this sub-section the surface treatments involved in the manufacture of bushings, namely cadmium plating, and passivation, are presented.

Passivation refers to the process of becoming a passive material, that is, less affected and corroded by the environment in which it will be used. When applied to stainless steels it increases the resistance to oxidation, and to the appearance of rust. The process consists in the removal of the free iron, which can result from the turning of the metal, from the surface of the parts. In this way it is possible to avoid an early deterioration of the amterial, since the presence of these contaminants constitute foci of possible corrosion. Removal is achieved by immersing the pieces in acid baths that allow the bound iron to be dissolved at the atomic level, obtaining a surface layer of chromium and nickel that later oxidizes, forming a layer that protects the stainless steel from corrosion. The standard that regulates the passivation of steel parts is the AMS2700, being able to be used two types of acids, the nitric and the citric. In the case of bushings these should be immersed in a solution of nitric acid, the concentration of which should be 25 % in volume at an average temperature of 27°C for at least 30 minutes.

The cadmium process consists of the application of a metallic layer of cadmium to the surface of parts. Cadmium is a soft blue metal, which when applied to steels, cast iron and copper, acts as a sacrificial coating, preventing corrosion from affecting the coated material. Corrosion protection can also be reinforced with the application of a chromium coating on the cadmium surface. In the process of manufacturing bushings, the electrodeposition of cadmium must be performed according to AMS-QQ-P-416. In addition, it is necessary to identify the type and class of treatment. The different types depend on the application or not of additional coatings, which may be chromium or phosphate. For the different types, these relate to the thickness of the coating which can range between 0.0002-0.0005 inches. In operational terms the process of deposition of cadmium is frequently carried out in cyanide baths, whose temperature should be around 30 °C, and the current density should be between 55-650 \( A/m^2 \). Associated with this process it may be necessary to perform two complementary procedures: the relief of tensions, and the relief of embrittlement by hydrogen. Relief of residual stresses consists of a heat treatment, which must precede the cleaning and coating of the parts, in order to prevent the occurrence of cracks during subsequent processes. The hydrogen embrittlement relief is applied to parts which have undergone heat treatments or whose ultimate stress is greater than 160 ksi and shall be carried out no later than 4 hours after the application of cadmium. Some of the materials not susceptible to this type of relief are: the aluminum and the corresponding alloys, and the 300 series austenitic stainless steels.
2.3. Heat Treatments

The heat treatments involved in the manufacture of bushings are: precipitation hardening, stress relief, and hydrogen embrittlement relief.

Precipitation hardening is a treatment used to increase the yield stress of a material and is used in a set of alloys of aluminum, magnesium, nickel, titanium and also in steels and stainless steels. The hardening process consists of a change in the solid solubility of the metal which, due to the increase in temperature, will allow the formation of new phase particles responsible for preventing the movement of defects in the crystalline structure of the metals. Being these responsible for the plasticity of the metals, when being reduced it is possible to increase the hardness of the metals. The occurrence of precipitation depends on two requirements: a high solubility of one component in the other, and a solubility limit that decreases rapidly in concentration relative to the main component with the reduction in temperature. These conditions are however not sufficient, it being necessary to carry out two thermal treatments in order to obtain the precipitates. The first consists in a thermal treatment of the solution, which allows all the solute atoms to be dissolved, obtaining a single solid phase of the solution, which after cooling allows to obtain soft materials. The second corresponds to the curing process, which consists in heating the material at a lower temperature than the first treatment, in order to obtain the precipitates by increasing the diffusion rates. In the manufacture of bushings, this treatment is associated with stainless steels and beryllium alloys, using elements of copper, aluminum, or titanium, to form precipitates. Due to the fact that the material supplied is already thermally treated with respect to the solution, it is only necessary to proceed to the second phase of the process, which is standardized for steel by AMS-H-6875.

The stress relief in the parts is carried out to reduce the residual stresses, and in the case of bushings, precedes the cadmium process in order to avoid the appearance of cracks during processing. The residual stresses never exceed the elastic tension of the material, and are caused when a body undergoes a non-uniform plastic deformation. The relief of stresses can be achieved by an annealing operation, which consists of in heating the parts at temperatures below the critical zone. As the residual stresses do not may exceed the yield stress, the plastic flow will reduce the residual stresses to the value of the stress at the temperature at which the stress relief is performed. In the particular case of bushings manufacturing, stress relieving operations are mandatory for steel parts subject to electrodeposition of cadmium and which have previously been subjected to to heat treatments with the aim of reaching hardnesses equal to or greater than 40 HRC.

Hydrogen embrittlement consists of the process of rendering a metal fragile through the diffusion of hydrogen from the exterior to the interior of the metal, and which may occur at various stages of the manufacturing process, such as in the application of coatings, or in electroplating operations. The susceptibility of a metal to the embrittlement depends essentially on its crystalline structure, being verified a greater vulnerability in the metals with compact hexagonal structure and cubic of centered body. In terms of materials, high hardness steels, aluminum, and titanium are the most vulnerable. Relief of embrittlement can be achieved by a process of annealing the parts, where the hydrogen is diffused rapidly at temperatures between 150-260°C. Regarding the bushings manufacturing process, this process should follow AMS2759 / 9, which defines the procedures necessary to eliminate the hydrogen introduced during the process of electrodeposition of cadmium in thermally treated parts, namely martensitic stainless steels whose hardness exceeds 34 HRC. Another relevant factor in this process is that the time of electrodeposition and the relief of embrittlement should not exceed 4 hours.

2.4. NDT-Non Destructive Testing

This sub-section will present the processes involved in evaluating bushings through non-destructive methods, such as inspection using magnetic particles, and use of fluorescent penetrants. If both tests are necessary, the the first step to be carried out must be inspection using magnetic particles, avoidance of contamination by fluorescent penetrants.

Magnetic particle inspection is used to detect the existence of surface discontinuities and the interplay of parts produced from ferromagnetic materials such as iron, nickel, and cobalt. This inspection must be done by the application of magnetic particles, while the area to be analyzed is magnetized. Since the maximum detection capacity occurs when the defect is perpendicular to the magnetic field used, at least two magnetisations, the magnetic field of which must be perpendicular to each other, must be performed. This procedure is standardized through ASTM 1444, which further establishes the particle concentration to be used, as well as the intervals at which it is to be inspected.

Inspection using fluorescent penetrants is a method to evaluate the existence of surface cracks that may compromise the integrity of parts produced from non-porous materials by applying a fluorescent dye. The standard setting out this procedure, ASTM 1417, also defines the type and level of sensitivity of the analysis. In the manufacture of bushings the analyzes are type I, which means that fluorescent penetrants are used, and sensitivity 3,
which corresponds to a medium level.

3. Lean Thinking
In this section we intend to present the concept of lean thinking, which is a management philosophy focused on the reduction and eventual elimination of waste in an organization. By waste can be understood all the activities that do not represent an addition of value to the final product.

The Lean concept was developed with the aim of making companies more competitive, efficient and flexible, thus giving them a greater capacity to adapt to changing market requirements. The principles that reflect this philosophy, initially defined by Womack and Jones [7], can now be defined as:

- Identify Value
- Map the Value Stream
- Create Flow
- Establish Pull
- Pursuit Perfection

Lean thinking can be schematized through the lean house analogy. The base consists of stability, heijunka (leveling of production), standard work, and kaizen (continuous improvement). The two pillars are the jidoka, which represents the ability to identify nonconformities in the process and correct them by looking for the source of the problem, and just-in-time, which represents the goal of reducing the amount of online stock of production. Through the implementation of the bases and the pillars it is possible to obtain a coverage that provides high quality products, lower production costs, and also shorter lead times.

The productive process can be divided into three categories of activities: value-added activity, incidental activity, and waste. The latter represents all activities that do not add value, and can be eliminated. Among the sources of waste identified, it is possible to enumerate the seven main ones, which are: overproduction, waiting times, transportation, overprocessing, excess inventory, unnecessary movements, and defects.

In order for the wastes listed above to be identified, and subsequently eliminated, it is necessary to know first what the value chain of the product is. The value chain corresponds to the set of all the actions necessary to produce a product, being initiated in the supply of the raw material and finished with the delivery to the client. The methodology for mapping the value chain consists of four steps, starting with the identification of the product, and then analyzing the current state and then preparing the future state. The next step involves implementation of the action plan, and subsequent improvement.

Another of the tools used to achieve the objectives of lean methodology is the 5 S’s. The term 5 S’s comes from five Japanese words that lead to a clean and pleasant work area. These words are: Seiri (Sort); Seiton (Set in Order); Seiso (Shine); Seiketsu (Standardize); Shitsuke (Sustain/Self-discipline).

In an ideal lean production environment, the production flow must be continuous, however, it is not always possible, and for this reason it is sometimes necessary to implement a system pulled by a supermarket. The use of this alternative may be due to high waiting times between processes, or situations in which unit production is not feasible. By implementing these systems, independent scheduling is avoided, and production is controlled by the customer. When it activates the production, information is generated to the supplier so that he can replace what was removed from the supermarket.

Finally, regarding continuous improvement processes, it is worth mentioning the iterative improvement method called PDCA (Plan, Do, Check, Action). This method is based on iteration, since whenever a hypothesis is confirmed (or denied), the execution of the cycle again allows to extend the future knowledge. In this way, it is possible to achieve great improvements in terms of performance, as well as kaizen, which represent minor improvements.

During the planning phase, you should evaluate the current process, or a new process, and understand how it will be implemented. In the implementation phase, the process defined in the previous step is implemented. Then the verification and evaluation of the implemented process should be carried out, as well as the expected results. Finally, in the correction phase, efforts should be made to improve the process by identifying the causes of the problems, or inefficiencies detected. The improvements achieved must be standardized so that the progress achieved is not lost.

4. Implementation
The implementation, in this case, consists in determining the current state of manufacture of bushings of the Embraer E170, and E190 aircraft. As the implementation of the general overhaul of landing gear for these aircraft was only undertaken in the summer of 2017, there was no process implemented for the manufacture of these aircraft bushings. Thus, the current state was based on the manufacturing process of bushings belonging to the Embraer ERJ145 aircraft.

The current Embraer ERJ145 train overhaul process consists of five stages: disassembly, cleaning, inspection, repair, and assembly. In the case of
manufacture of bushings, their production must be started after the expert opinion, which corresponds to the end of the inspections. At this stage, it should be the production scheduler checking the need for bushings as well as their existence in warehouse or not. If production is required, this is done in multiples of 10 units, depending on the number of units used per landing gear, which clearly confirms an overproduction situation. Next, it is the responsibility of the production planning, the amount of material needed, as well as whether it should come in the form of man or wafers. Subsequently, the production project is opened and the engineering department responsible for drawing up the work letters is required if the bushing to be produced has never been produced internally.

4.1. Accounting and characterization of bushings

Landing gears are made up of two sub-assemblies: the main landing gear (MLG), and the nose landing gear (NLG). The MLG consists of two symmetrical sets, each having the following sets: MLG Locking Stay, MLG side Stay, MLG Downlocking Stay, and MLG Shock Strut. The NLG, at the forefront of the aircraft, has the following sets: NLG Shock Strut, NLG Drag Brace, and NLG Locking Stay. These are NLG Shock Strut and MLG Shock Strut, which represent the majority of the required number of bushings, with a share of approximately 60%. In total terms, the number of bushings for the Embraer E170, and E190, aircraft are, respectively, 282, and 327.

The distribution of bushings materials used in both aircraft can be verified in the figures 1 e 2, where the percentages are presented as a function of the total number of bushings. When visualizing these images, we can verify that the most used materials are Al-Brz alloys, and precipitation hardened steels. 1-Brz alloys are used in applications that require a combination of corrosion resistance, excellent rolling properties at high loads, and high strength both at high temperatures and at room temperature. Precipitation-hardened steels are used in applications requiring high cross-strength and toughness.

4.2. CNC equipment

The equipment available for the turning of the bushings, is a lathe of the North American manufacturer HASS, more specifically the model ST-10, that is represented in the figure 3.

Among the characteristics of this equipment the following stand out: the size of the mandrel, and the capacity of the bar. As the maximum size of the mandrel is 165 mm, then this will correspond to the maximum length of the bushings with production capacity. The capacity of the bar influences the way the material is to be supplied, if the bushing has a diameter greater than 44 mm it should be supplied in the form of wafers, otherwise it may be supplied as a bar.

4.3. Productive constraints.

Production constraints can be divided into four groups: inability to perform treatments, lack of technical drawings of the bushings, constraints on the size of the bushings, and logistical and planning problems.

Some of the bushings required in the revisions require an operation of applying a PTFE coating, which due to the reduced coefficient of friction allows to reduce friction and wear. In global terms, the influence of this constraint can be observed in Table 1.

The absence of technical drawings is an impediment, since without them it is not possible to obtain information on their manufacture, such as the dimensions and the necessary treatments. Table 2 shows the influence of this constraint.
Table 1: Bushings with PTFE coating.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Quantity</th>
<th>Acquisition Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>E170</td>
<td>25</td>
<td>4.94%</td>
</tr>
<tr>
<td>E190</td>
<td>40</td>
<td>10.83%</td>
</tr>
</tbody>
</table>

Table 2: Bushings without technical drawings.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Quantity</th>
<th>Acquisition Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>E170</td>
<td>2</td>
<td>0.22%</td>
</tr>
<tr>
<td>E190</td>
<td>7</td>
<td>2.48%</td>
</tr>
</tbody>
</table>

Regarding bushings dimensions, the main constraint is their length, which should not exceed 130 mm. The maximum diameter should also not exceed 130 mm in order to ensure correct attachment of the material. The impact of this limitation can be seen in Table 3, around 5% of the total bushings.

Table 3: Dimensional constraints.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Quantity</th>
<th>Acquisition Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>E170</td>
<td>12</td>
<td>31.02%</td>
</tr>
<tr>
<td>E190</td>
<td>15</td>
<td>28.18%</td>
</tr>
</tbody>
</table>

The main limitations in terms of logistics and planning are related to the ordering and delivery of raw material required for manufacturing. The first shortcoming is the high delivery time of the material, which is around 60 days. In addition to this, there is a difficulty in obtaining the necessary wafers for the manufacture, since the equipment of cut present in the company does not allow to obtain precise cuts. Some of the obtained wafers can be seen in Figures 2 and 3, a waste verifying that varies between 20–40% in the effective part comprimento. As an alternative to cutting equipment, the company may have recourse to an outside supplier, however this will mean an additional waiting time of 30 days.

Figure 4: Cuts obtained in the company.

Figure 5: Cuts obtained in the company.

5. Results

In this section it is intended to present the results, and for this, it is divided into three sub-sections: drawing up the work letters, implementing the system using a supermarket, and finally, counting the economic benefits arising from the adoption of internal manufacturing over external acquisition.

5.1. Work letters

In the elaboration of the work letters there is a set of information that is mandatory, as for example: the identification of the part-number, and the manual referring to the component where bushing is going to be installed. In addition to these, in any task, it must be indicated the description of the task, the performance that is responsible for its execution, the necessary training of the operator that performs it, and finally, it must be indicated the expected time of accomplishment of the task. In Figure 6, we can see an example concerning the definition of a task.

In the elaboration of the work letters there is a set of information that is mandatory, as for example: the identification of the part-number, and the manual referring to the component where bushing is going to be installed. In addition to these, in any task, it must be indicated the description of the task, the performance that is responsible for its execution, the necessary training of the operator that performs it, and finally, it must be indicated the expected time of accomplishment of the task. In Figure 6, we can see an example concerning the definition of a task.
One of the information that the work letter must tell, is the amount of material needed, namely the length. The formula for calculating the length varies depending on how the material is made. If it is in the form of a bar, the following expression is used:

\[ L = 10 + Qty \times (L_{bushing} + 5). \]  

(3)

If, on the other hand, the material is supplied in the form of wafers, then the total length calculation is calculated by:

\[ L = Qty \times (L_{bushing} + 10). \]  

(4)

The remaining processes involved in manufacturing must be followed according to the information contained in the technical drawing, and therefore each work letter is unique. Despite this, it is possible to verify a set of common procedures, depending on the material of the bushings. In figure 7, we can see which procedures are common for the two largest sets of materials, Al-Brz alloys, and precipitation hardened steels.

5.2. Pull system with supermarket

Once the bushings with manufacturing capacity have been identified, it is necessary to implement a system that allows their production in an efficient and expeditious manner.

Due to the impossibility of implementing a pull system, mainly due to the limitations on the supply of raw material, it is necessary to use a supermarket that allows an immediate availability of material. In the supermarket there was both wafer and bar material. In the supermarket there was both wafer and bar material. In the main document can be visualized the tables indicating the quantities of material required for both aircraft. The tables are divided according to the material and the aircraft to which they belong, and it is also possible to visualize the rod to be used, as well as the length and quantity of material per each wafer and bar. In Figure 8, an example of such tables can be viewed.

<table>
<thead>
<tr>
<th>Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply raw material</td>
</tr>
<tr>
<td>Cut of material</td>
</tr>
<tr>
<td>Overhaul</td>
</tr>
</tbody>
</table>

Regarding the capacity of the shop, it can only carry out the general review of two landing gears of the aircraft analyzed. Therefore the possible combinations are: 2 E170, 1 E170 + 1 E190, or 2 E190.

Taking into account that the maximum capacity of the workshop is two E170 / E190 landing gears, and that its review, as well as the supply of material takes about 90 days, we can conclude that the supermarket should have enough material to carry out three of aircraft. Accordingly, two separate supermarkets should be set up for each aircraft, and each of these must possess material necessary for three landing gears.
5.3. Waste accounting
Associated with the production of the bushings, there is a quantity of material that although necessary for the fixation of the bar, is not actually used in the manufacture. In relative terms, on average, the excess material corresponds to about 37% of the required length of a given rod. Larger values occur in situations where the number of bushings to be produced is reduced, or in situations where the length of bushings is reduced.

5.4. Cost analysis
In this section, we intend to account for the company in terms of costs, which is the expected benefit from the adoption of the internal manufacturing process compared to the external acquisition.

For reasons of confidentiality, it was decided not to present the costs in absolute terms. In Figure 9, we can verify the influence of the acquisition costs of the bushings with and without manufacturing capacity, for the total cost of acquisition of the bushings. The acquisition costs of the bushings with manufacturing capacity represent about 60% and 55%, respectively, for the Embraer E170 and E190 aircraft. The remaining percentage corresponds to the cost related to the acquisition of bushings without manufacturing capacity.

Figure 9: Contribution of the cost of bushings with capacity and without for the total cost.

The values shown in the figure 9, are calculated taking into account that the acquisition is performed in non-urgent situations. In AOG-Aircraft on Ground situations, average acquisition prices are higher. In the Figure 10, the relationship between the average purchase price, the price for AOG situations, and the average cost of internal manufacturing can be found. The acquisition cost in AOG situations is 1.4 times higher when compared to the average acquisition cost, while the internal manufacturing cost is around 50%. The average cost of internal manufacturing was determined based on an internal study of the company, regarding the bushings produced for the Embraer ERJ145 aircraft train. From this value, it is possible to obtain a reference for the expected cost for the bearings of other aircraft.

Figure 10: Comparison between average price of acquisition, AOG price, and manufacturing price.

Given the average manufacturing costs, and the number of bushings with production capacity, it is possible to calculate the expected benefits in terms of costs. In Figure 11, it is possible to visualize the final cost with the adoption of internal manufacturing relative to the purchase cost of all the bushings. In the column referring to the cost of manufacturing, the total value corresponding to the production of the bushings with internal manufacturing capacity is presented, this value being obtained by multiplying the average cost per bush with the quantity of bushings with production capacity.

Figure 11: Relative comparison between the total cost of purchase and the cost related to internal manufacturing coupled with the purchase of bearings without capacity.

In the case of the Embraer E190 aircraft, the impact of domestic production is more significant, resulting in a gain of 18%, which is due to the fact that it has a larger number of bushings with internal manufacturing capacity. Despite this, the Embraer E170 aircraft still has a gain of approximately 10%.
as shown in the column referring to the joint purchase and manufacturing costs of the figure 11.

6. Conclusions

In an increasingly competitive market, and with the expected increase in world air traffic in the coming decades, it is likely that there will also be an increase in the requirement for MRO companies, such as OGMA. These companies must have mechanisms that allow them to offer a quality service, but which is also expeditious and financially competitive.

In the project developed in this dissertation, the objective was to analyze the manufacturing process of bushings used in the general revisions of the already industrialized trains, and from this to develop the necessary tools to implement the system of production of bushings for the aircraft Embraer E190, and E170.

In order to implement the manufacturing process, the first step consists in the elaboration of the work letters, essential for the production process. In preparing them it was possible to identify the existing limitations, such as the need to apply PTFE coating, lack of technical drawings, and constraints related to bushings dimensions. In terms of logistics and planning, the main constraints are related to the time of supply of the material, and the cutting of the material, which implies a high waste of material.

In order to make the process more efficient, and less dependent on the delivery time of suppliers, it was decided to implement a supermarket with enough material for three landing gears of each aircraft. The cutting of the material is performed by an external entity, and is provided in the form of rod or wafers, depending on the outside diameter, thus minimizing material waste to a minimum. If the cut was done in-house, the waste would be between 20-40%.

When implementing the supermarket, the company is less dependent on external suppliers, and can act immediately in the face of a need. Previously, this need was anticipated, leading to overproduction, and consequently additional costs. Another of the benefits of the supermarket was the decrease in the variability of the rod diameter, since the diameters were selected so that they could be used in both aircraft.

Finally, with the adoption of internal manufacturing over external purchasing, cost savings of 20% for Embraer E190 and 10% for Embraer E170 are expected. Again, this system allows for increased competition through cost reduction, which can be passed on to the customer by reducing the cost of maintenance or used by the company for other investments.

6.1. Future work
As future projects it is suggested to implement the system of production of bushings using a supermarket, as indicated in the results. After implementing it, and assuming a prospect of continuous improvement, inefficiencies must be identified and corrected.

Since the Embraer E175, and E195, aircraft are derived from the analyzed aircraft, the differences should be verified and the study performed on the materials and quantities required, as was done for other aircraft.

Once the system has been implemented for the Embraer E170 and E190 aircraft, and the anticipated benefits have been verified, the same system must be used for the trains of other aircraft that also carry out their general revisions, namely the Embraer ERJ145 and the Lockheed C-130 Hercules.

In conjunction with the implementation of these production systems, further measures should be considered to reduce the time required for inspections. In this way, it will be possible to increase the workshop’s current capacity, and consequently the company’s competitiveness.

References