



ELECTROIMPACT E6390 RIVETING MACHINE ? PRODUCTION RATE INCREASE STRATEGY

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Instituto Superior de Engenharia do Porto
Department of Mechanical Engineering – Industrial Management



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Dissertation presented to Instituto Superior de Engenharia do Porto in order to fulfil the necessary requisites to obtain the degree of Master, in Mechanical Engineering, realized under orientation of Professor Doctor Maria Antónia Gonçalves.

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Department of Mechanical Engineering – Industrial Management



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Palavras Chave

Eficiência; Produtividade; Rebite; Qualidade;

RESUMO

Atualmente, as linhas de produção industriais de aviões enfrentam novos desafios. As pessoas estão a viajar mais do que nunca, os bilhetes de avião estão mais baratos do que nunca, a população mundial está a aumentar e, portanto, a procura por novos aviões, especialmente as de corredor único tem portanto, aumentado. É por isso que as taxas de produção são fundamentais neste setor, onde as máquinas são muito caras e é necessário tirar o melhor proveito de cada uma delas, para que o grande investimento possa ter retorno o mais rápido possível e para que as indústrias aeronáuticas tenham capacidade de oferta para a crescente procura. Alguns fabricantes têm um livro de encomendas para os próximos 10 anos, e continua a crescer. Surge assim, a proposta para estudar a eficiência da revitadora da Electroimpact E6390 com maior preponderância para os processos mais complexos e demorados, mas também para novas alternativas e procedimentos, que poderão ser implementados no âmbito do Mestrado.

Nesta tese, será feita uma visão geral da máquina que estamos a estudar, mostrando os principais processos e recursos, para que os leitores possam entrar em contexto. Depois, vai ser feita uma análise de um programa executado recentemente, para que possamos entender onde é desperdiçado mais tempo. Com isso, será iniciada uma análise de produção, vão ser procuradas as maiores perdas e vão ser dadas propostas para transformar os processos menos bem conseguidos em processos mais eficientes.

Conseguiu-se apurar então que existe um elevado número de variáveis que podem influenciar a qualidade dos processos, a duração e a complexidade dos mesmos. Isto tem implicações ao nível de hardware, software, logística, materiais, recursos humanos, planeamento, estudo do processo, estudo dos tempos, entre outras. Conseguiu-se também demonstrar a importância de várias ferramentas de qualidade, gestão, planeamento, ferramentas Lean, e ainda a qualificação de pessoas, e com isto mostrar os efeitos que cada medida relacionada com cada um destes tópicos, traria em termos de eficiência. Neste caso sem desprezar a qualidade do produto. Também existem outros departamentos da empresa que desempenham um papel importante, mas às vezes não é tão visível. Processos como logística de mercadorias e informações serão tidos em consideração, pois não há eficiência se a máquina estiver à espera de material. Quanto mais rápido a informação chegar às pessoas, mais rápida será a resposta, portanto este tópico também será trabalhado.

Por fim perceber que é necessário fazer intervenções a vários níveis. Começando pelo planeamento, não só de produção, mas também de logística e o fluxo de informação. A formação rigorosa dos recursos humanos é de uma importância extrema e deve ser contínua. Passando ainda pela introdução automática de ferramentas Lean, é possível ter indicadores em tempo real que auxiliariam a equipa de engenharia nas decisões. Podem ser melhorados os tempos, e o planeamento da manutenção, e ainda deverá ser pensado o custo/benefício homem máquina, uma vez que um recurso extra pode trazer ganhos consideráveis.

KEYWORDS

Efficiency; Productivity; Rivet; Quality;

ABSTRACT

Presently aircraft industrial production lines are facing new challenges. People are travelling more, flight tickets are cheaper, world population is increasing, and so the demand for new aircraft, especially single aisle aircraft. This is why the production rates are fundamental on this industry, where the machines are very expensive, and it is necessary to get the most out of each one, so the large investment can be paid off as soon as possible, and so aircraft industries can supply for the increasing demand. Some manufacturers have a 10-year backlog and growing. That's how this proposal rises, to study the efficiency of the Electroimpact Riveting machine E6390, with focus on the most complex processes but also on new ways and procedures, that can be implemented, in the ambit of this Master degree.

It will be made a general overview of the machine we are studying, exploring the main processes and resources, so that readers can understand and contextualize. Then an analysis of an executed program will be made, to understand where the main losses on the production are. These will trigger a production investigation, where the main losses will be quantified, and new proposals of improvements suggested.

Was possible to observe there is a considerably high number of variables that can act on the quality of the processes, the duration and complexity of them. These has implications at several levels, like hardware, software, logistics material, human resources, planning, study of processes, study of times, among others. Is was also possible to show the importance of several quality, management, planning and Lean tools and Human resources qualifications. Was possible to highlight the effects of each action related to each of those topics, would bring to the efficiency of the machine. Of course, these actions would assume maintaining the high quality of the product made. There are also other company departments that play an important role here, but sometimes it is not as visible or traceable. Processes like logistics of goods and information will be taken in account because there is no efficiency if the machine is waiting for material. Along with these suggestions, new features will be proposed, and new industrial techniques will be suggested, to assist engineers. The faster the information gets to people, the quicker the response will also be considered.

It was clear the knowledge that a handful of interventions needed to be made. Starting with the planning, not just production planning but also logistics and flux of information.

Human resources training is one of the most important keys to success and should be a continuous process. Implementation of several Lean tools would allow a real time overview of the process and production, for example, and help sustain decisions. Times and processes can be improved, and the relationship cost/profit between men and machine needs to be revised. Maintenance can be better planned, with introduction of maintenance 4.0.

LIST OF SYMBOLS AND ABBREVIATIONS

List of Abbreviations

AC	Aircraft
ADU	Advanced Drilling Unit
CAD	Computer Assisted Design
FF	Flex Fixture
NC	Numerical Control
OEE	Overall Equipment Effectiveness
OOT	Out Of Tolerance
PNs	Part Numbers
RMR	Rate of Material Removal
VSM	Value Stream Map

List of Units

Kg	Kilograms
mm	Milimeters
inch	Inches
ft	Feet

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INTRODUCTION

1.1 CONTEXTUALIZATION

1.2 OBJETIVES

1.3 FRAMEWORK

1 INTRODUCTION

1.1 Contextualization

A proposal was made to study the Electroimpact riveting machine E6390 production rates, where we would identify the main issues of the process, and based on what we learn, give a list of proposals to improve its efficiency.

Efficient companies always look to outperform on their productions lines, and get the best out of the machines and human resources. Therefore, it is necessary that each operator stands to be as efficient as possible, and this project will work around how it is possible to achieve that, by using the most available tools at our disposal.

This machine has a big impact on the production of the aircraft panels. With the machine it is possible to automate thousands of hours of labour work, make it of high quality and repeatable. I can't think of another way to do this specific job without this machine.

It is known that this machine is performing under the expected rates. When Electroimpact says this machine is supposed to build 2 panels per week, and customers only manage to do half of that, then an alarm should be raised. We will use this inefficiency as a trigger for new improvements. This gives extra importance to this topic, because it will use many of the tools learnt on this degree, and it is a good opportunity to study this machine in real production.

We will work together with Electroimpact in order to collect as much information as possible:

- Items, processes and cycle times;
- Observe the operators in a daily basis, without interfering on the job;

Pay close attention to all of the machine and operator's needs, among others.

This information will be processed with the help of the ISEP (Instituto Superior de Engenharia do Porto) coordinator and Electroimpact coordinator. All of the details should be part of this document.

1.2 Objectives

The main goal of this project is to perform a study of the Electroimpact Riveting machine, identifying its inefficiencies, in order to improve productivity of the work place, focusing on the optimization of the machine.

It is intended to identify the causes of the inefficiency, either by the machine, the process, the human resources, the planning, the supply chain, and others.

Potential solutions will be proposed to help reduction and/or elimination of the identified root causes.

To help sustain some of the proposed changes, the rough cost savings of each solutions (at least the ones possible to calculate) will be presented.

1.3 Structure

In order to clarify this dissertation, it was defined the next structure:

Introduction: In this chapter, the subject will be introduced, with a short framework overview, the objectives of the work development, the structure and methodology.

Literature Review: This chapter will contain the technical literature that will support a better understanding of the machine and its processes. This will mostly come from theoretical concepts, books, published scientific articles, some of which are more practical to better understand the process, and some more scientific to support the choices for the industrial management methods.

Development: At this phase, the practical side of this master thesis will be shared. A collection of data will be gathered, from the backlog of the machine production, as well as the record of the operator's workplace and movements, and studying its inefficiencies. Using the insights from the previous chapters and the collected data, the interpretation of the results will be detailed, and the main outputs would come from the treatment of all this info.

Conclusions: An overview of the results, as well as the main actions to take in a way to get the best out of the machine.

Bibliography: The articles and resources used to strengthen this thesis and to learn concepts, will be identified here.

LITERATURE REVIEW

- 2.1 DRILLIGN PROCESS
- 2.2 BOLTING AND RIVETING
- 2.3 SETUP/PLANNING
- 2.4 CALIBRATION
- 2.5 LEAN MANUFACTURING/AUTOMATIC MODE
- 2.6 RESOURCES AND SUPPLIES
- 2.7 QUALITY
- 2.8 DEBUG AND QUALIFICATIONS
- 2.9 PROCESS CAPABILITY - CPK
- 2.10 COMPUTER SIMULATION
- 2.11 MAINTENANCE 4.0

2 LITERATURE REVIEW

With typically over 2.3 million parts, attached with over 3 million fasteners, it may be surprising to learn that approximately two out of every three fasteners on a twin aisle aircraft are fastened by hand. In addition, the fasteners are often installed in locations designed for strength and not necessarily ergonomics. These facts lead to vast opportunities to automate this tedious and repetitive task (Ryan Haldimann, 2019).

Productivity enhancement is a process to achieve higher levels of output while consuming the same or less amounts of input resources. Also if the same output level is reached in a shorter time period, it indicates improved productivity. It is in this respect that projects designed to improve productivity must also consider time as a key resource.

Automated manufacturing systems perform operations such as material handling, processing, assembly or inspection with a reduced level of human participation (Csanyi, 2016).

The automation definition in general “implies operations or acting, or self-regulating, independently, without human intervention” (Nof, 2009). When automatic control was added to mechanization in the 1950s the advantages of automation became clear (Nof, 2009).

Besides robotics, automation includes numerically controlled machining centres, dedicated automatic assembly machines and other special purpose machines (Appleton & Williams, 1987). There are several reasons for automation of manufacturing processes.

The most common are:

- Productivity increase in terms of production rate or labour productivity by operating at high speed and capacity;
- Reduction of labour cost by replacing manual activities;
- Improvement of product quality due to more constant process parameters and the elimination of human errors;
- Reduction of manufacturing lead time and response time;
- Elimination of repetitive and fatigue manual tasks and thereby improvement of working conditions and ergonomics;
- Improvement of operator safety in case of unsafe environments;
- Feasibility of certain processes that require e.g. high precision or miniaturization. (Beyer, 2004) (DeVlieg & Feikert, 2008).

The introduction of automated fastening to the manufacture of legacy aircraft is often desired to provide improvements in quality, production cost, and worker ergonomics, among other factors. Special challenges to automation are frequently encountered in these applications (Burton Bigoney, 2017).

Like an airplane that only adds value to its owner when it is flying, the main fight of the airliners is to reduce the ground time while this machine adds as much value to our customers when is actually drilling panels, our (and our partners) fight, to keep it running at all costs.

2.1 Drilling Process

2.1.1 Drilling Concept

In the aerospace industry, all structural parts are joined together with bolts or rivets. This mean, that an aircraft has thousands of bolts and rivets, and consequently thousands of holes.

Tools, in this specific case, drill bits, are a very import part of this process. The combination of many factors, like the quality of the tools, the geometry, the final treatments, the velocity of approach to the material, the rpms of the tool and lubrication are essential for a quality hole.

To be able to define all those parameters, we need to get to the RMR (Rate of Material Removal) ($N.m^2$), (Ramy Harik & Thorsten Wuest, 2019). Typically, *RMR* can be determined as the “uncut area” A (m^2), multiplied by the force towards the material f (N). The uncut area, in square meters, is a circular area dependent on the tool diameter:

$$A = (\pi \cdot d^2)/4$$

Equation 1 - Uncut Area (Ramy Harik & Thorsten Wuest, 2019).

The *RMR* is then ($N.m^2$):

$$RMR = f \cdot A$$

Equation 2 - Rate of Removal (Ramy Harik & Thorsten Wuest, 2019).

$$F = m \cdot a$$

Equation 3 – Force (Ramy Harik & Thorsten Wuest, 2019).

The power required to perform the operation can be performed through two methods:

- 1- Multiplying the cutting force F_c (N/m^2) and the cutting speed V (m/s);
- 2- Multiplying the *RMR* by the specific energy of the material u ;

$$P_c = F_c \cdot V = u \cdot RMR \text{ (Kw)}$$

Equation 4 – Cutting Power (Ramy Harik & Thorsten Wuest, 2019).

The time required (T_m) for a drilling operation can be computed as the RMR as noted before.

Although this Electroimpact riveting machine has multiple axes, the drilling operation only uses one. After the machine does the normalization to the panel, and on the right coordinates, then only one axis is going to work to perform the hole drilling. Despite the many involved factors, this process is known to have reduced complexity, low cost, fast processing speed, and is easy to achieve good dimensional results.

Reaming is also part of this drilling process, and it can be achieved in many ways. On a traditional drill press this is done with a reamer, used after the hole is nearly on the final diameter. Here, on this riveting machine, the tools are ready to final drill/reamer the hole to very tight tolerances. Figure 1 is an example of tools storage.



Figure 1 - Typical format of AC part drilling tool

There are three ways of drilling those holes: Manual drilling, Semi-Automatic drilling, and automatic drilling. A quick explanation will be given to each process, with our focus on the automatic drilling.

2.1.1.1 Manual Drilling

This is how a good percentage of the holes are done on aircraft parts, mostly on small components, where a machine can't reach. In this topic we talk about manual drilling,

we are still talking about precision and quality holes once current techniques and tools have been improved.

The key to this success is a combination of good drill bits, stability on the process, and stability on the parts being drilled. It is essential that the system is well engaged with the AC (Aircraft) parts.

On this process, made by operators, a hole is drilled in a few steps. Each manufacturer has his own standards, but the main idea is to start with a small diameter and grow to the final diameter.

On the Figure 2, below, is a good example of a good manual drill:



Figure 2 - Manual Drilling Tool (AP Tools, 2018)

A precision drilling template is used with the same hole pattern of the AC part, and it is used to guide the handle bushes that will guide the drill bits. Each drill bit size will have its own specific made handle bush.

2.1.1.2 Semi-Automatic Drilling

This is an improvement to the manual drilling. Still not possible in a few confined places, but where possible, it is faster, cheaper (when we speak in a price per hole), safer and with improved quality.

This process also needs a drilling template and locking pins, similar to the manual process, but instead of an operator, a machine drills and countersink the holes. It is possible to program this kind of machines, and set each of the parameters, including rpm, advancing speed, countersink depth, etc. Refer to Figure 3 for an example of this process.



Figure 3 - Example of an ADU drilling with a drilling template (Setiteck, 2019)

Below, on Figure 4, is an example of semi-automatic drilling. This sample is from a company called Seti-Tec that has been developing this type of machine, and they have come up with this new electric ADU (Advanced Drilling Unit).

Seti-Tec éVo range

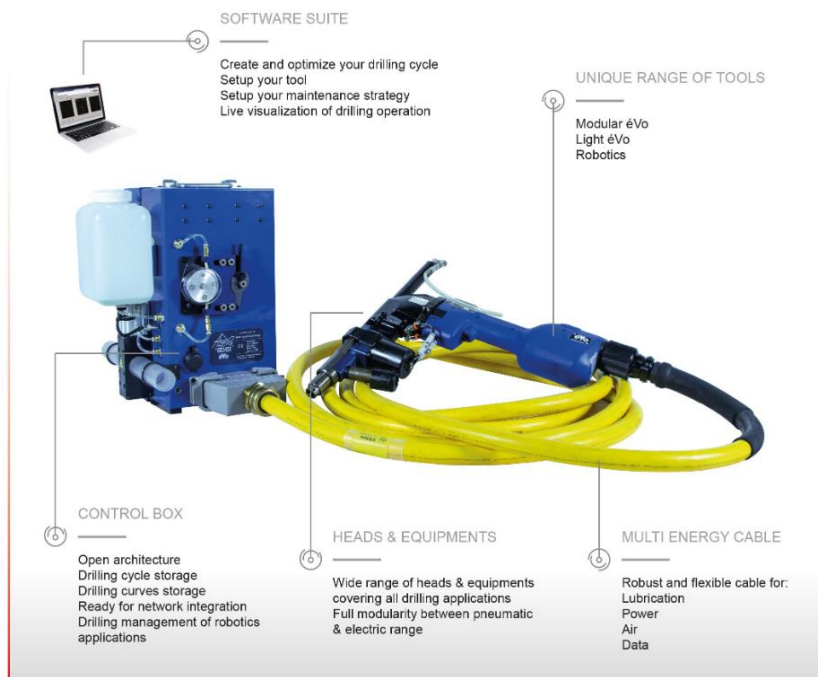


Figure 4 - New Seti-Tec Electric ADU (Setiteck, 2019)

This machine incorporates a vacuum to remove the drilled aluminium. This ADU produces holes of a much higher quality than the ones drilled manually, but they also have a better quality of drill bits. They are the choice of most of the AC manufacturers for the locations of the AC parts where they can't fully automate.

2.1.1.3 Automatic Drilling

This is where our machine E6390 is involved. The CNC controlled mechanism allows a high precision hole, with the best quality and at an impressive rate. Obviously, the machine is the main focus on this process, but it also crucial to use high quality drill bits as explained before.

This type of automation is very important because it is very hard to have people drilling thousands of holes by hand, especially if we are talking of high rates of production. Aircraft wing panels are a good part for automation, where we have easy access, large surfaces and thousands of holes. Many of these holes are countersunk, requiring more care and precision so the rivets or bolts don't get too deep or too high, something that directly influences the surface quality and the capacity for lift and fuel consumption.

This machine is a new improved version of machines like E4000, capable of accurate positioning of the toolpoint. On the E4000 machine the toolpoint is the point where the drill first touches when entering the skin. The E4000 is designed to locate this point within .008" over the work envelope of the machine, (Dr. Peter Zieve, 1997).

With this machine we can set all parameters, and optimise them in a way, where we can drill the best holes in the shortest period of time. With the automatic record of all parameters and actions, studies can be done at any time, and continuous improvement team has here a small laboratory to work on and to innovate the existing processes. Follows on Figure 5 a CAD picture of the machine.

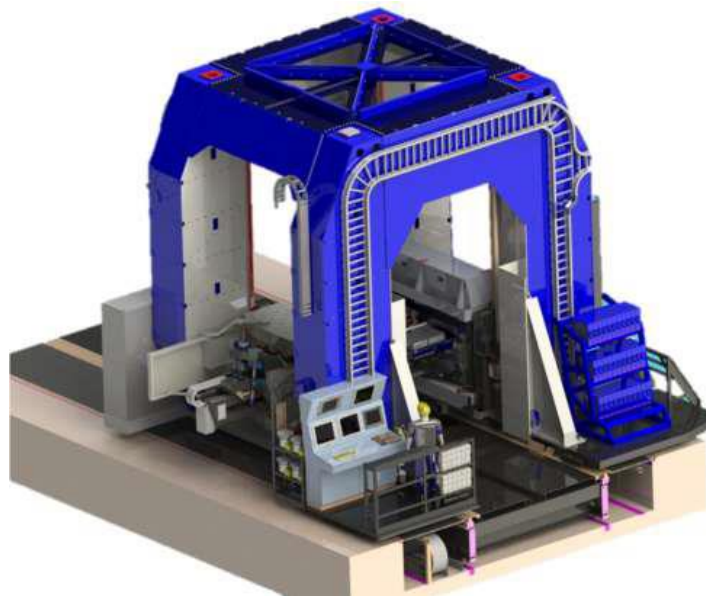


Figure 5 - Machine structure overview

To meet the demands of high production rate the production has to be effective and have low lead times. This is done by having balanced stations where products have low

waiting and minimum movement between stations. Drilling and fettling operations will take a certain time, depending on material and dimensions of the holes (Nadim Bitar & Linus Gunnarsson, 2010).

On this thesis, this full automated drilling machine will be shown in more detail, in order to understand the potential of this automation. On Figure 6 is an overview of the machine and Flex Fixture.



Figure 6 - Machine and Flex fixture overview

2.2 Bolting & Riveting

2.2.1 Riveting

The most common methods to join AC parts together is by riveting or bolting them. Fasteners are defined as a commodity of components used in many manufacturing industries. They are basically hardware devices that mechanically join or affix two or more objects together (Florent Texier, 2009).

With new carbon fibre structures, new processes arise, like bonding, but when our main material is aluminium, those initial processes still rule.

Successfully riveting aerospace fatigue-rated structure (for instance, wing panels) requires achieving rivet interference between a minimum and a maximum value in a number of locations along the shank of the rivet. In unbalanced structure, where the skin is much thicker than the stringer, this can be particularly challenging, as achieving minimum interference at the exit of the skin (D2) can often be a problem without exceeding the maximum interference at the exit of the stringer (D4). Softer base materials and harder, higher-strength rivets can compound the problem, while standard

manufacturing variations in hardness of part and rivet materials can cause repeatability issues in the process (Curtis Hayes, 2016).

This squeeze riveting machine, as its process implies, squeezes the back side of the rivet to properly add the two material, which the rivet protrudes. This one uses both type of rivets, depending on size, and part of the panel to be joined. Basically it can follow any customer specification (Peter Zieve, 2019). On Figure 7 is an example of the two most common types of rivets.

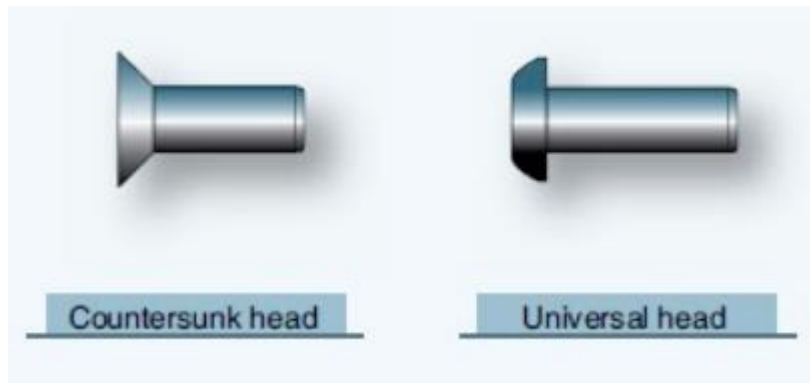


Figure 7 - Rivert – Countersunk and Universal (Dr. Peter Zieve, 2019)

Each manufacturer has the capacity to customize each parameter of the machine. The force of approach, the force applied on the tight fit holes, the squeeze force, and so on. This is more complex than we would initially expect. There are many relevant factors behind the quality of a rivet/bolt. In the next couple of pictures, Figure 8 and 9, it can be seen a good rivet, and a not so good rivet, where the countersink is too deep and is not flush with the panel. This is not ideal for the aerodynamics.

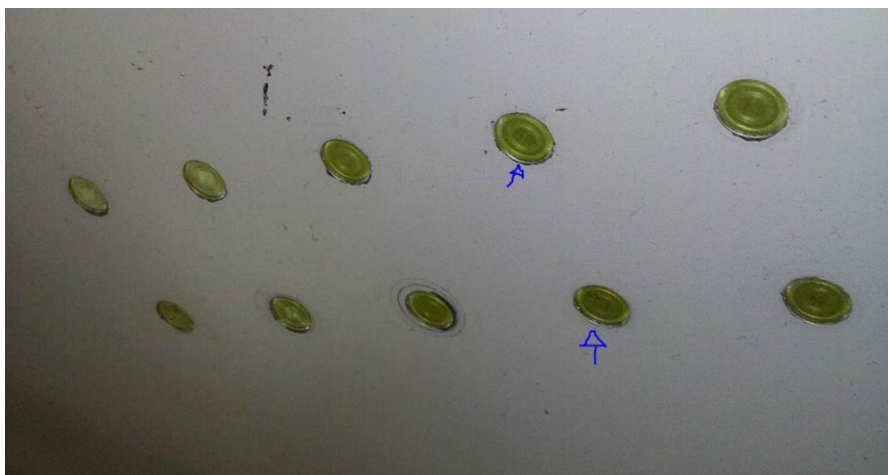


Figure 8 - Rivet too deep into the panel - countersink hole too deep

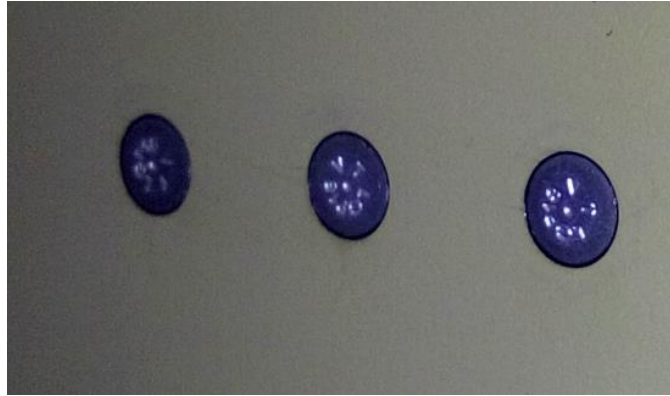


Figure 9 - High quality rivet - flush with the panel

In the case of the rivets, the back side should look like the ones on the next picture, Figure 10. It is also visible on the same picture how a good hole should be on the back side (exit of the drill). No burrs are visible, being this a “clean” hole, as expected with this type of technology and process automation. This is a very important detail, because, once this is a fully automated system, there is no operator going back and deburr the hole.



Figure 10 - Rivet - Back side

Rotorcraft airframes are complex structures designed to satisfy different goals, (A. Manes, M. Giglio, F. Viganó, 2015); fatigue life represents one of the most critical issues, which must be guaranteed throughout the design and the construction phase. In this scenario riveted joints play an important structural role especially because of the

variable loads they are subjected to. Their fatigue behaviour is strictly influenced by the local stress fields left very near to the holes during riveting manufacturing operations.

The effects of the squeeze force, the clearance, the rivet length and the clamping angle in the stress field of the joints are considered by means of numerical models.

Results of another study reveal (Tomasz Machniewiczza , Andrzej Skorupaa , Adam Korbel) extremely complex dependencies of the specimens' fatigue properties on riveting process related factors and add to the necessity of using strongly empirical fatigue life prediction approaches for riveted joints.

2.2.2 Bolting

Another way of join AC parts together is by bolting them, using a bolt and a collar, like on Figure 11.

This machine is capable to supply both the bolt and the collar, and fit them together.

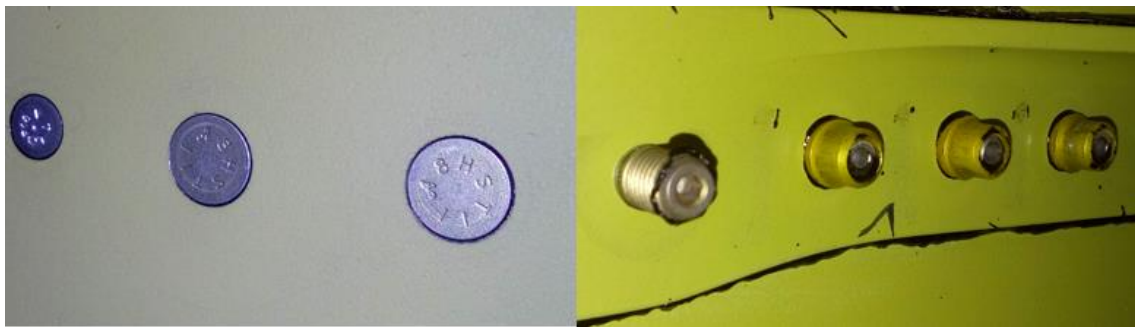


Figure 11 - Bolt - Front side and back side

By determining the stresses acting in the bolts and their failure modes, it is possible to minimize the structural weight of the connection mechanism. For example on the structural analysis of the fuselage concept, the axial stresses in the bolts are caused by the pressurization of the cabin and the longitudinal bending moment over the fuselage (Q.P.D. van Keymeulen, 2015).

The shear due to the payload and fuselage mass must be carried by the bolts. They fail when the shear force reaches the material's shear strength.

In this specific case, we refer to skin/stringer connection. The primary function of the wing skin is to form an impermeable surface for supporting the aerodynamic pressure distribution from which the lifting capability of the wing is derived. These aerodynamic forces are transmitted in turn to the ribs and stringers (T. Megson, 1999). In Figure 12 is an example of bolts.



Figure 12 - Aerospace Fasteners (Dr. Peter Zieve, 2019)

Inspection of fasteners prior to installation is critical to the quality of aerospace parts. Fasteners must be inspected for length/grip and diameter at a minimum. Inspecting the fasteners mechanically just prior to insertion can cause additional cycle time loss if inspection cannot be performed at the same time as other operations. To decrease fastener inspection times and to ensure fastener cartridges contain the expected fastener a system was devised to measure the fastener as it travels down the fastener feed tube. This process could be adapted to inspection of fasteners being fed to the process head of a running machine eliminating the mechanical inspection requirement and thus decreasing cycle time (Ryan Haldimann, 2016).

2.3 Setup/Planning

Prior to the production start and setup, the operator and all teams somehow involved on this process, need to prepare the machine. This depends on the AC part that is going to work on, and the program it is going to start with. That is where the planning starts, and a schedule begin.

The overall idea when designing the schedule is to start the first day in the shipping area, continue the next day to finishing area and so on. The material flow was followed from the end until the beginning. It can be described as a reversed walk through the factory and is done to keep the customer's point of view in mind as well as increase the understanding of how the products, with all of its different components, were manufactured (Erlach, 2013). To gain knowledge of how the products moved within the factory, and at the same time visualize the waste as unnecessary transportation described by Hines & Rich (1997), a spaghetti chart is constructed (Olhager, 2013).

When an operator starts the production, they need to carry out a number of checks, mostly for material, but also regarding the machine state. There are two lines here:

- a) Setup of the material the machine is going to consume;
- b) Setup of the machine tools;

For the material setup, this will be explored on the topic “Resources and Supplies”.

All the tools need to be properly cleaned. This included the resync camera.

One of the main features of this machine, is the FF (Flex Fixture). This is a fixture that has the capability to adapt to many different panels, for different AC, in case of low rates, and this way using the same machine for multiple programs.

If high rates are expected and several machines have been installed, then a different approach is taken. Custom fixtures are made for each panel and this fixture would only receive this panel. The lower panel would have its own specific fixture as well. This could be done in a line, where the same machine reaches two or more fixtures, or individual cells can be made. The most efficient way is to have two fixture per machine, even if the same panel, due to the times used, for some companies, to install the panel, do small fixes, have the quality team checking and running tests, etc. Below on Figure 13 is the Flex Fixture control station.



Figure 13 - Flex Fixture main controller

The operator needs to select the panel that is going to be drilled, and this will trigger the proper information to each post of the FF. After that, operator needs to press a button in each post, until the respective one drives himself to the final position, in all X, Y and Z axis.

The manufacturing process begins with the creation of the NC programs using the offline programming application (Carl Landau, 2016).

Before the drilling process starts, operators need to get the right NC programs to load into the machine. These programs may suffer specific/isolated changes if something on the process was altered, or if for some reason a selection of holes will not be drilled, etc.

The choice of the sequence of the programmes is important. The number of operations in the different workstations vary and also the WIP as well as distances around the cell. Distances were needed to calculate cost-savings of reduction in travel when comparing current state with suggestions for a future state. All of the data needs to be gathered with the purpose of being used in a value stream map (VSM).

According to Keyte & Locher, 2004, the types of metrics that are used in a VSM can vary from case to case but processing time and lead time are two metrics that must be in the map in every occasion. Alongside these two metrics and mentioned earlier; changeover time, value adding time and waiting time have to be added to the VSM to create an extensive view of all of the different components that the overall lead time consists of (Anton Kamne, Anton Sjoberg 2016). This is then accompanied with information about the number of operations per workstation. This is information that facilitates identification of unevenness in the production process, i.e. if a workstation has more or less work compared to the amount of operations in it (Liker, 2004). Since this information either did not exist in the system or the quality of the data was too poor, it has to be collected manually. On Figure 14 we can see how the machine should look like.

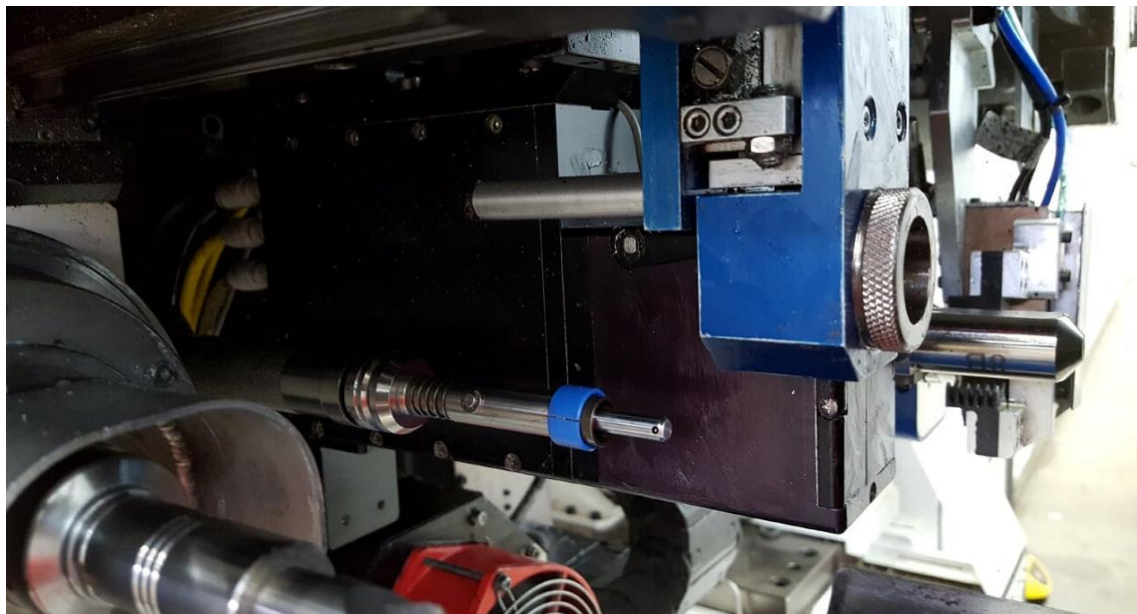


Figure 14 - Tools aligned on the machine – ready for production

It is visible most of the tools used on this process. From the left to the right, it is the drill bit, the probe, resync camera (inside the big black box), and the bolt inserter.

It is expected, that:

- 1- For FF jigs, that this setup is done in parallel with the jig loading, to better utilize a stoppage.
- 2- All the possible test and calibration to occur within the same interval of time (excluding the changes done within the same build).
- 3- Operators need to be aware of the tools to be used at each time, and have them ready prior to use.
- 4- For machines working with custom fixtures, the loading/unloading of the panel is not so critical, once the machine would, ideally, never stop, and the time used for drilling an entire panel, would be more than enough for all of the side works to get the second panel ready to go, and so, the setup becomes more critical, once now that's the only thing stopping the machine. More resources might be needed in parallel with the operator.

It is expected, that on the development of this thesis, new improvements arise, in order to cut downtimes, and overlap as many tasks as possible.

2.4 Calibration

Components like resync camera, normality sensors, drill bits and probes must be calibrated from time to time. The manufacturer of the part, the customer or the manufacturer of the machine defines the calibration frequency. Drill bits are calibrated by drilling a coupon, and measuring both the diameter and countersink. The coupon stand is showed on Figure 15, below.



Figure 15 - Coupon stand with a sample half drilled

The probes are calibrated using a specific high precision tool. The measured diameter must match the true tool diameter (within a defined tolerance).

There is another kind of calibration. The one calculated by the machine, using the resync camera. This is the way to shift the machine's position, to best match the position of the aircraft datums.

Machine calibration is then defined as the process of improving the machine's accuracy by changing the machine positioning software, rather than changing its physical design. More concretely, it is the process of identifying a better relationship between its joint readings and the actual 3D position of the end-effector. (Manuel Ribeiro, 2017).

Camera calibration is the essential process of determining the internal camera geometrical and optical characteristics (intrinsic parameters) and the 3D transformation (position and orientation) between the camera and the world's coordinate system (extrinsic parameters). (Manuel Ribeiro, 2017).

The intrinsic parameters of a camera, internal and optical characteristics of a camera, are required to model the way light travels through the lenses up to the plane of the sensor.

The extrinsic parameters are the transformation from the camera to a world's coordinate system. If the camera is fixed, then this is a simple transformation camera-to-world, but if the camera is attached to a movable machine than two transformations are required, camera-to-machine and machine-to world. The process of estimating the

transformation camera-to-machine is called hand-eye calibration. Camera calibration techniques can be classified into two categories: photogrammetric calibration and self-calibration. In photogrammetric calibration (R. Tsai, 1987), (Z. Zhang, 1999), (R. K. Lenz and R. Y. Tsai., 1988), (P. F. Sturm and S. J. Maybank, 1999), an object whose geometry in 3D is precisely known is used, while in self-calibration techniques (S. J. Maybank and O. D. Faugeras, 1992), (Q.-T. Luong and O. D. Faugeras, 1997), no object is used. Instead, simply by moving a camera in a static scene two constraints can be made in the intrinsic equation. While photogrammetric is more stable and efficient, self-calibration is more flexible, but less reliable. It is also important to state that a camera calibration heavily depends on the camera's lenses. Therefore, any adjustment of zoom (focal length), focus, aperture or any other optical aspect of the lenses will result in an invalidated camera calibration and different intrinsic and extrinsic parameters.

2.5 Lean Manufacturing\Automatic Mode

This machine is designed and programmed to be able to follow the NC program autonomously. This includes all of the processes, including tool changing, bolt or rivet selection, etc.

On this mode, the machine has to change the tool, each time the program swaps to a new diameter hole, or a new diameter rivet (each has its own tools). The tool holder is on one end of the machine which means that it may need to move up to 28 meters to swap a tool, and then move 28 meters back in the worst scenario. Best scenario is still a move of at least 8 metres.

Later in this thesis, alternatives will be given to improve the tool change process. The main goal is to find the best compromise between automatic mode and operator mode. It is a fact this machine is highly automated, but to make it more efficient, a well-trained operator has a significant role to play.

The NC programmers also have an important role, optimizing the programs to minimise the frequency of tools changes and total distance travelled. Below on Figure 16 is the tool holder.



Figure 16 - Tool holder – with bolt insert tool

Lean manufacturing has a high importance on this process. The main goal of the machine operating automatically is to minimise stoppages, and move at the fastest rates. This is only possible if the principles of the Lean manufacturing are present.

The “5s” organize the work area, (sort) eliminating what is not needed, (set in order) organizing what is essential, (shine) keeping the area clean, (Standardize) and (Sustaining) those. (Niko Immonen, 2016).

The “Bottleneck Analysis” is essential to improve the slowest processes, and also to allow a good application of the takt times. (Axel Ericson, 2017).

The “Continuous Flow” helps eliminate the waiting time, inventory and transport. (Bjorn Visser, 2009).

“Gemba” is a philosophy that reminds us to get out of our offices and spend time on the factory floor, where the real action happens. (Lunds Tekniska Högskola, 2016).

“Just in Time” pulls parts through production based on customer demand instead of pushing parts through production based on projected demand. (Katsiaryna Kazak & Wing Yee Choi, 2019). It relies on many lean tools, such as Continuous Flow, Heijunka, Kanban and Standardized Work.

Although “Kanban” could be an interesting tool, for regulating the flow of goods, it may not be applied directly to this study where an empty shelf may not mean the need for more material.

The “KPIs” are a way for engineers and stakeholders to quantify the effect of all other tools. Aligns with the top-level strategic goals, are effective at exposing and quantifying waste and readily influenced by plant floor employees. (Mikael Falck & Fredrik Karlsson, 2011).

“Muda” means waste. It is used to eliminate the processes that do not add value to the process. (Anton Kamne & Anton Sjöberg, 2016).

The “OEE”, that will be used below on this work, gives us a good relationship of Availability, Performance and Quality. Combined they give us a perception of how well our process is performing. (Keegan Muluh Cheh, 2013).

“Poka-Yoke” is used to eliminate the error. This can either be applied to a tool (machine tool), or a process, as long as clears all the possible failures modes. (Iris D. Tommelein & Sevilay Demirkesen, 2018).

The “Root Cause Analysis” is a problem solving methodology. It incentivises the employees to find the root cause of the problem, instead of just fixing it. Helps to ensure this specific problem does not occur again. (Tommi Tikka, 2011).

“Six Big Losses”, the Six categories of productivity loss that are almost universally experienced in manufacturing: Breakdowns, Setup/Adjustments, Small Stops, Reduced Speed, Startup Rejects and Production Rejects. Provides a framework for attacking the most common causes of waste in manufacturing. (Xiaomeng Sun, 2018).

“SMART Goals”, Specific, Measurable, Attainable, Relevant, and Time-Specific, helps to ensure that goals are effective. (Tørresdal Ingunn, 2016).

“Standardized Work”, helps to keep best practices and eliminate waste. (Tørresdal Ingunn, 2016).

“Takt Time”, defines the pace of the production. It aligns demand and production rates, and tend to eliminate both, bottlenecks and excessive production. (Hallvard Øystese, 2019).

The “Total Productive Maintenance (TPM)” is an approach to maintenance that focuses on proactive and preventative maintenance to maximize the operational time of equipment. (Xiaomeng Sun, 2018).

“Value Stream Mapping”, as mentioned previously in this work, is a tool used to visually map the flow of production. It exposes waste in the current processes and provides a roadmap for improvement. (Hultman Jens, 2018).

Lean tools if properly used, would eliminate the next two main issues:

- 1- The back side tools need a frequent maintenance, due to the amount of drill waste, sealant and lubricant that can be accumulated on them after drilling hundreds of holes. Operators need to ensure they are well maintained before returning them to production. On Figure 17 is a properly clean rivet backside tool.

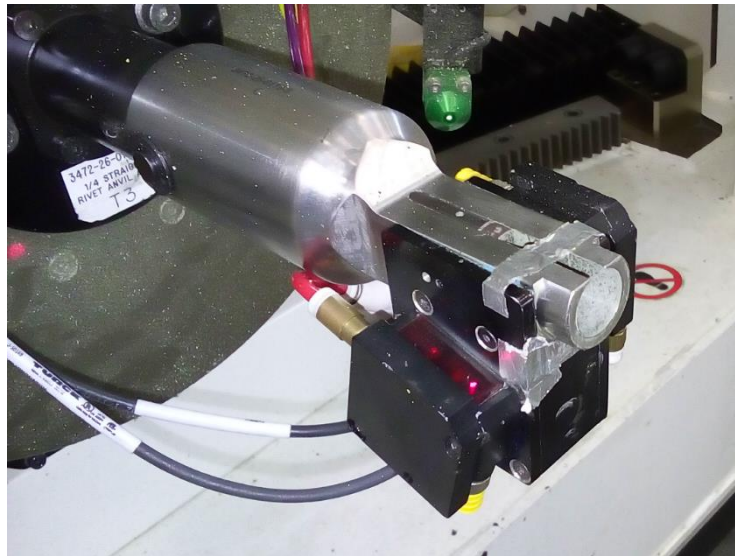


Figure 17 - Rivet Backside tool

- 2- Another important tool of this machine is the resync camera, and this one should also be kept clean.
- 3- To accurately locate the fastener the vision system must first be calibrated. This is done using machine learning techniques to determine the 12 parameters per camera to fully define the transformation between a camera 2D image space and physical 3D space. These parameters can be broken into two groups; 6 extrinsic parameters that define the location of each camera to the physical world and 6 intrinsic parameters that define characteristics of the camera and lens setup. Intrinsic parameters define the focal length of the lens, scaling of pixels, image offset and a radial distortion coefficient for the lens. Extrinsic parameters define the position and rotation of the camera in space (Ryan Haldimann, 2019).

More processes are improved when Lean manufacturing takes place.

2.6 Resources and Supplies

Due to the high rate of this machine (hundreds of bolts a day) a very efficient system is needed to fully feed the machine.

A big number of supplies are needed every day, and every hour, to feed the machine. Now, this means, a good logistic systems needs to respond quickly and efficiently to all of the needs, and good planning needs to exist (Zuckerman, A. (2002). On Figure 18, is one of the shelves where some items are stored.



Figure 18 - Sample of shelves that need to be filled prior to a production

For each panel that is manufactured, engineers and operators know exactly how many bolts, rivets, nuts, sealant deposits, tools, etc are going to be needed. Adding complexity, when we consider bolts or rivets, we refer to several diameters, and sometimes, several lengths per diameter. (Rediger, J., Fitzpatrick, K., McDonald, R., and Uebele, D., 2015).

With this, it is clear that a deficient supply chain system will directly affect the machine rate, no matter how fast the machine is, because with no supplies, the machine doesn't have the consumables needed to build the AC panels (Mentzer, J. T. (2001).

Later on, the daily issues of supplying this machine will be approached more carefully. Even when a large variety of parts is required, there must always be enough stock to keep the machine running.

Human resources are also a key factor in the process. It is possible to make a machine free of operators, but this one does need a person to run it. This person\operator needs to be comfortable with the machine, and able to understand what the machine requires. This comes with skill, training, and persistence. This is not a simple machine, due to its complex systems, and due to the amount of operations it does. So many things can escape from the normal path, and the operator needs to be on top of it, understand what causes an alarm or an error, and how to properly fix it, or what to report. Most of the issues found are related to AC parts NOT OK. This might be because the machine is programmed to drill a specific stack thickness but if the aircraft has been reworked and shimmed, the machine will detect the difference and raise an alarm. This is just an example of the things that can happen during production, and that can keep the machine stopped, if the customer neglects the need\importance of good and well trained people running the machine.

Note that an operator has many tasks, to keep up with the machine. Not only does he have to run the machine but also change the backside tools, feed bolts and nuts, clean and maintains all tools, properly prepare the sealant, feed all the F2C2 (independent system used to feed the machine with fasteners), set up the FF to the right panel and independently move each post as well as keep the machine clean, etc. During the development of the analyses, we expect to provide a solution to allow the operator to complete successfully his tasks, and at the same time, allow the machine to run. The main goal of our customer must be having a machine constantly working, and our goal is to develop a machine that the minimum break time possible.

When trying to build the most cost-efficient supply chain, it all comes into play. Having good access – in terms of location as well as infrastructure – to different transport modes, widens the opportunities for your business (Lysons K., & Farrington B., 2020).

On Figure 19, is the F2C2 system.



Figure 19 - Sample of shelves that need to be filled prior to a production

2.7 Quality

According to ISO 9001:2015, a properly implemented quality system needs to demonstrate its ability to consistently provide products and services that meet customer and applicable statutory and regulatory requirements; and aim to enhance customer satisfaction through the effective application of the system, including processes for improvement of the system and the assurance of conformity.

One of the critical goals of automation is repeatability with quality, two things a human can't do, on this type of job. This machine is subjected to an enormous amount of tests, where pretty much all parameters can be adjusted, in order to produce the best quality holes, insert rivets and bolts with high precision, install sealant and inspect its own job on the go.

The latest fastening process uses a ballscrew to produce the squeeze forces needed for forming rivets or bolt collars. The new process is achieved using a combination of force and position control and is capable of forming up to 40,000 pounds of force at rates of up to 200,000 pounds per second while holding the part location to within +/- 10 thousandths of an inch (Sean Hollowell, Joseph Elsholz, Michael Assadi, 2015).

Key factor for this quality, is a good calibration, as explained before on this work. Another important thing is the quality and state of the tool. It is important to respect the specification of the manufacturer of the drill bits. Even this can extend the tool life. Precisely to find this, and other deviations to the perfect condition, this machine can be set to inspect has many holes as the customer desires. Every time a hole is OOT (Out Of Tolerance), an alarm is raised, and operators must investigate further. Depending on the dimension of the deviation, this can only be observed for a while, and monitored, meaning, that one "imperfect" hole, might not be a serious issue. Collares are feed to the machine via the system below, on Figure 20.



Figure 20 - Colars feeding system

Beyond the size of the hole, surface roughness and other geometric features can be equally important. Poor surface quality or improper alignment may lead to stress concentrations once the fasteners have been installed (Campbell, 2006).

Holes which do not meet the tolerances can be costly. (Daniel Hallberg and Patrick Ringdahl, 2017). A hole which is too small can be reamed to the correct size with relative ease, but a hole which is too large must be re-drilled with a larger diameter and the fastener replaced with an oversized dimension. An oversized hole will affect future repairs since the hole can only be enlarged to a limited extent before compromising the strength of the part (FAA, 2012). Any oversized holes must be documented and may result in a discount to the final selling price of the aircraft.

In the Figure 21, we can see a coupon, used to calibrate the machine to get the best holes. As previous showed, deep countersink holes lead to rivets and bolts either too high on the panel, or too low.

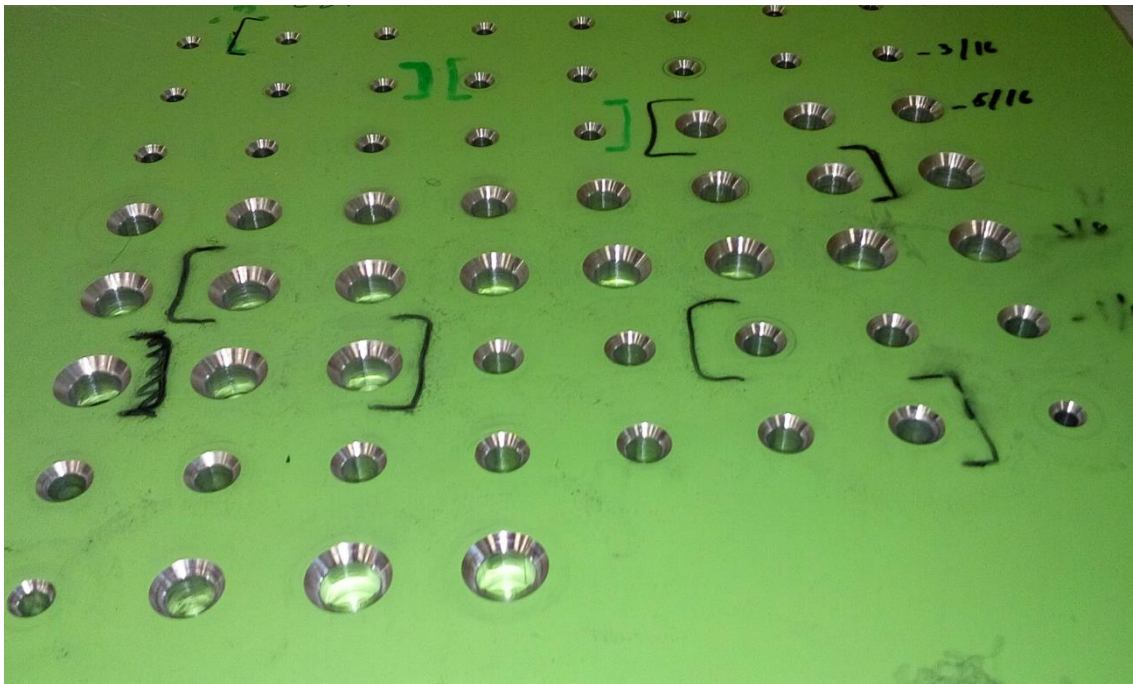


Figure 21 - Test Coupon

Countersinking is the process of machining a cone shaped recess in the material to create a conforming mating surface for a fasteners head, without significantly weakening the material. The most common countersink angle for aerospace applications is 100° (FAA, 2012).

Once the fastener is inserted in the hole, the head is embedded into the material and the surface should be flush. This is crucial when riveting parts of the fuselage and wings since any deviations from a smooth surface will disturb the airflow. (Daniel Hallberg and Patrick Ringdahl, 2017).

Drilling technology has seen significant improvement over the last decade, and today, there are a vast number of papers explaining the best way to calculate the force, velocity of advance, rpms, etc, to produce the best possible hole. The specific cutting force varies largely depending on what material and grade of that material is being cut. Empirical studies performed by cutting tool manufacturers have been compiled into tables (Appendix A: Specific cutting 20 force) showing the specific cutting force for a chip of 1 mm thickness and 1 mm² cross sectional area. This is a material specific constant denoted $Kc1$.

The position of each hole is also extremely important, and customers expect the final product to be as similar to their CAD (Computer Assisted Design) as possible. But, because of the highly complex processes of machining, shot peening, among other involved processes, a 20 meter long panel, or several of over 10m in length, it is known that they will never arrive in the nominal position. Based on artificial vision, machine can where cameras localize the tack they are looking for and best fit the machine to the new nominal position. Laser sensors, largely to guide the backside tools, compliment this process.

This machine has also an amazing precision, driven by strong and reliable servo motors, good scales, and a careful installation using laser trackers to set all rails and racks into a near perfect flat and straight line. Every aspect of the machine is responsible for the quality of its performance. This is not just a matter of having good motors and scales. The whole structure has to be properly designed to accommodate the weight and forces of the mechanism and the AC part, and a use of the best materials available on the market.

In Industrial management, on the topic of quality, several tools help achieve the best possible process:

- 1- Cause-Effect Diagram (Fishbone Diagram)
- 2- Check Sheet
- 3- Control Chart
- 4- Histogram
- 5- Pareto Chart
- 6- Matrix Analysis
- 7- FMEA

The fishbone diagrams present the constructs and corresponding individual key success factors which lead to an identified problem. The constructs are illustrated in the red boxes where the underlying individual key success factors and their symptoms are represented in in the smaller branches, indicating causality. (Yetener, I., 2017).

The next diagram, Figure 22 identifies the root cause of an OOT hole.

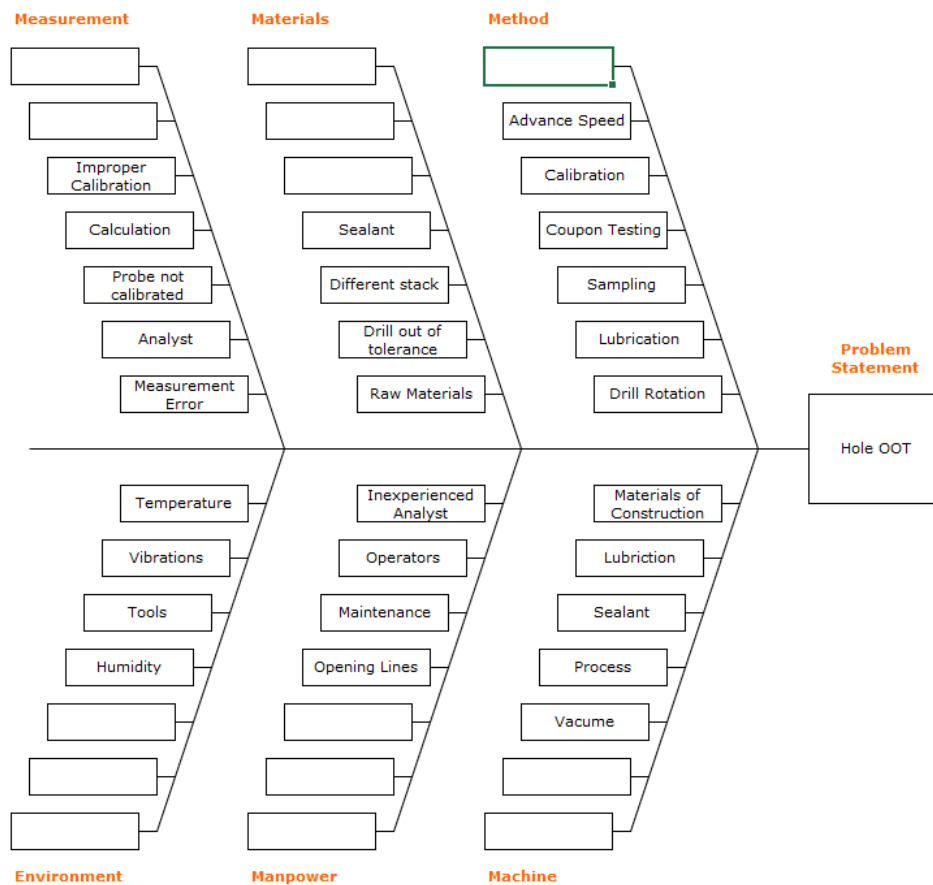


Figure 22 - Cause and Effect Diagram - Hole OOT issue

Simple “Check Sheets” are the basic tool for data collection. The data is then used for different purposes: to assist in understanding the actual situation, for analysis, for process control, for regulating data and for acceptance or rejection of data (Dan Lisai, 2018).

“Control Charts” are an easy way of showing trends over time, and how a process is performing. Control charts use the mean and standard deviations to measure whether a process is statistically in control or not. And if it’s not, it’ll show when it’s happening. (Josph Hubert Ault, 2013).

Moving forward with this work, on the development phase, it will be interesting to apply some values form the machine data, generate a Control Chart, and find some conclusions.

In the database context, a data distribution is a listing of value-frequency pairs of some attribute. “Histogram” is a mechanism used to provide the approximation of frequency for a given value (point query) or value range (range query) without storing or accessing the whole original data distribution. (Li Wang, 2017). More precisely, given an attribute X , a histogram on this attribute is constructed by partitioning the data distribution of X into $\beta (\geq 1)$ mutually disjoint subsets called buckets and storing the statistics information and bucket boundaries for each bucket. In each bucket we have the following attributes:

many different factors to take into account. This makes it a great technique to use in almost any important decision where there isn't a clear and obvious preferred option (Richard Edgar Hodgett, 2013).

“Decision Matrix Analysis” works by getting a list of options as rows on a table, and the factors that need to be considered as columns. Then a score is given for each option/factor combination, weight this score by the relative importance of the factor, and add these scores up to give an overall score for each option. (Richard Edgar Hodgett, 2013).

“Failure modes and effects analysis” (FMEA) is one of the most practical design tools implemented in the product design to analyse the potential failures and to improve the design. The practice of FMEA is diversified and different approaches are proposed by different organizations and researchers from one application to another. But, in this specific case, we are analysing the process. (Hua-wei Wen, 2013). So, this would be a (PFMEA) “Process Failure modes and effects analysis”.

A diversified team would get together and analyse the most important failure modes of the process, score each one of them, and start by implementing improvements for the critical ones.

2.8 Process Capability - Cpk

Measuring a process' performance and acting upon the assessments based on the measurements are critical elements of any continuous quality improvement efforts (Spiring, 1995). Companies, mostly on automotive industry, make assessments of process performance based on different indicators. It is more relevant, the most quantity produced, and therefore car makers that produce millions of sample, tend to invest a lot on this tools. Most common of these indicators can be described in terms of process yield, process expected loss and capability indices of a particular process characteristic (Chen, et al., 2001). Among these indicators, Process Capability Indices (PCIs) have gained substantial attention both in academic community and several types of manufacturing industries since 1980s (Somerville and Montgomery, 1996; McCormack Jr, et al., 2000; Kotz and Johnson, 2002; Wu, et al., 2009). This increase in popularity is mainly because companies require some numerical indicators of how well the process is performing regarding its specification limits (Anis, 2008).

The first process capability index proposed in the literature is the Cp index, which is defined as:

$$C_p = \frac{USL - LSL}{6\sigma}$$

Equation 5 – Cp Index Equation (Duygu Korkusuz, 2011)

where USL and LSL denote the upper and lower specification limits, respectively, and σ is the standard deviation of the process characteristic of interest. The Cp index measures the process spread in relation to its specification range. Since Cp does not take the process mean of the quality characteristic into account, it does not give any information about whether the process is centred (Bordignon and Scagliarini, 2002).

In order to overcome this problem, a second-generation PCI, the Cpk index, is introduced. The Cpk can be defined as:

$$C_{pk} = \min\left[\frac{USL - \mu}{3\sigma}; \frac{\mu - LSL}{3\sigma}\right] = \min[C_{pu}; C_{pl}]$$

Equation 6 - Cpk Equation (Duygu Korkusuz, 2011)

where μ and σ are the mean and the standard deviation of the quality characteristic studied, respectively (Duygu Korkusuz, 2011). The mean of the process characteristic has an influence on the Cpk index and therefore it is more sensitive to departures from centrality than the Cp index (Anis, 2008). The Cp and Cpk indices are the most used process capability indices in industry and they are called standard or basic PCIs (Deleryd and Vännman, 1999; Kotz and Johnson, 2002; Anis, 2008). The earlier practical applications of these basic PCIs require the fulfilment of two assumptions:

- The process must be in statistical control.
- The process characteristic of interest must be normally distributed.

At aircraft industries the rates in terms of final product are very small relative to automotive industries. But this study can be interesting if we look at this in a different perspective. For example, the number of panels produced every month, can be between 4 and 10, depending how the machine is performing, but the number of drilled holes is between 12.000 and 30.000. In this case the study won't apply to the specification of the panel, but to the specification of each drilled hole.

In practical application and literature, confusion between process capability indices (PCIs) and process performance indices (PPIs), and about their notations (Cp, Cpk vs. Pp, Ppk) can sometimes rise. Although these two indices aim at indicating the performance of a process, they differentiate the estimations of the indices that are calculated. For standard PCIs, Cp and Cpk, the standard deviation of a process is estimated within sub-

groups by using control charts. Since it uses the variation within sub-groups, this type of estimation measures the short-term variation of a process. Even though many academicians prefer the estimation of long-term variation for process capability calculations, the notation C_p and C_{pk} is widely used in literature (Duygu Korkusuz, 2011).

2.9 Debug and Qualifications

In factory automation, elimination of down time is considered one of the most critical components for producing a quality product on budget. For this reason, keeping a production machine fully operational always is required. No machine is free from failures, so eliminating the time to recover is the best method to maintain productivity, explains Skye Jenkins, Electroimpact controls engineer. The first line of defence is the machine operator. If the machine has a fault during operation, it is the responsibility of the operator to attempt to recover from the fault and continue production. Unlike most automated factory environments, we do not have a dedicated team of maintenance technicians available 24/7 to assist and support. This puts 100% responsibility on the operator to keep the machine operating.

Operator station is presented on Figure 24, below.



Figure 24 - Operator station

One of the more common errors witnessed was incorrectly running lines in the part program. If an operator is unfamiliar with G-Code, it can be quite simple to drill into an existing titanium fastener. Not only does this damage an expensive part, but it will often shatter the drill, requiring the operator to replace the cutter. They can often skip a cycle as well, which if goes unnoticed, will require manual processes later in the production line. Another significant addition to down time.

In parallel with this issue, is the quality of the programs. Not just can the operator be running the wrong line, but also the program can have some defects. Programmers can assign the wrong bolt to a specific program, or forget to select one bolt, or even work with an old CAD. It is also programmer's responsibility to get the best and fast way to drill the work piece. This has to be done before the program is used. The right sequence of programs is also case of study, prior to production, to get the best of the several combinations used on each panel.

Collar feeding system issues are often seen. The collar present sensor would often get dirty, and provide false positives on collars being loaded. If an operator is familiar with the system, this is a 2min fix. If unfamiliar with the feed system, this could be hours of downtime trying to identify what sensor has failed, and how to fix it.

This tool, illustrated on Figure 25, shall be part of a routine check, where operator go check all tools after use, and put them back to original conditions. It is expected that the machine operator is capable of cleaning the tools, and also the routine maintenance required.

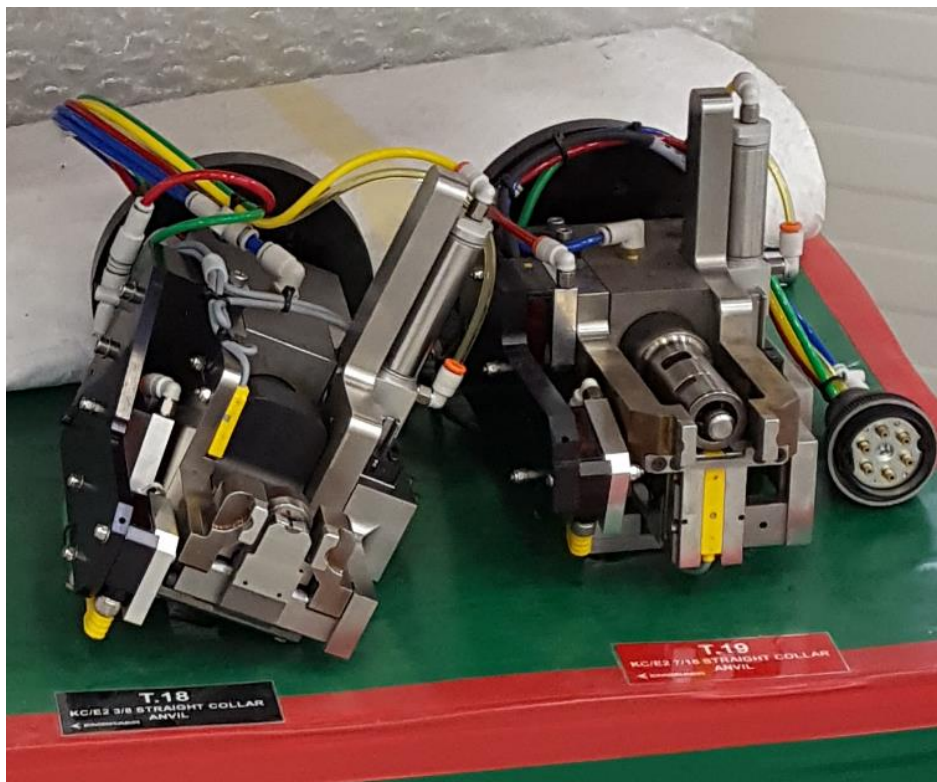


Figure 25 - Collar inserter - Backside tool

The calibrations, one of the topics considered before, is essential to this machine, and can cause troubles and time losses later in the process if not done properly. All operators are expected to know how to properly execute this task (Russell DeVlieg, 2010).

The selection of the human resources to deal with this machine is random, but an effort shall be made to find people with good background and willingness to learn, to better serve the company needs (Ecclestone, K. 2006).

In theory, all the possible errors shall be in the operator's manual, and how to properly solve them, but with this complex system, new issues can arise. A new operator would need months, before he is able successfully to run the machine on his own. This does not mean a new person cannot deal with the machine, but it means that it will be stopped at any small issue says Zack Luker, Electroimpact controls engineer. It is key to have people properly trained in not just how to run the machine, but also how the entire AC assembly process works.

The employee who receives the necessary training is more able to perform in their job. The training will give the employee a greater understanding of their responsibilities within their role, and in turn build their confidence (Cherylm M. J., 2020).

Most employees will have some weaknesses in their workplace skills. A training program allows them to strengthen those skills that each employee needs to improve. A development program brings all employees to a higher level, so they all have similar skills and knowledge (Cherylm M. J., 2020).

2.10 Computer Simulation

In the future society, unnecessary use of resources will be minimised. This affects both development of new products and use of existing ones. Integration of sustainability aspects in product development is therefore gaining more and more interest (Hallstedt S., 2008). Fortunately, it has been shown that product development, including prototyping, can be made more resource efficient by so called virtual prototyping (Jönsson A., 2008). Virtual prototyping takes advantage of the fact that most of the behaviour of a product can be simplified and described by mathematics (Thomke S.H., 2003). The mathematical relationships can be implemented into computer models, so-called simulation models, and solved numerically. The solution reflects certain aspects of the product's behaviour. It has been shown that virtual.

Within this case of study, customers can supply a CatPart full of information, where suppliers can find rivet/bolt sizes, stack dimensions, type of rivet/bolt, space between holes, and so on. Computer simulations allows companies to join together the machine

and AC part to be worked. This allows a perfect alignment between them and a perfect overview of the actions taken by the machine. To note, that in real life nothing is perfect, and so it is expected that not all works exactly the same way as on a computer simulation.

A substantial amount of research has been done showing the potential of using simulation in product development (Hisham M., Abdelsalam E. & Bao H.P., 2006). The potential is especially high when it comes to development of complex products which have behaviours that are hard to foresee intuitively. Products in short series or expensive products like aircrafts or customized machine tools can also benefit from simulation support during development. A major advantage of building simulation models of not yet existing products is that they can be used in optimisation studies. This ensures that the physical product will perform as good as possible under some given circumstances.

The integration of mechanical engineering, electrical engineering and information technology is known as mechatronics (Isermann R., 2005). The development of mechatronic products is less intuitive and puts new demands on the product development process (Verein Deutscher, 2004).

Product development can be seen as an iterative decision-making process (Wall J., 2007) and it is important that well-informed decisions are made throughout the whole product development process. Experimentation can enable good decisions by raising the level of knowledge about the studied system.

Physical models can, for instance, be scale models or early prototypes built to give knowledge about one or many studied properties. Virtual models can be mathematical models solved either analytically or more often numerically (Nicholas Lum, 2014). On Figure 26 is an example of how a setup models looks like to simulate the drilling/riveting process.

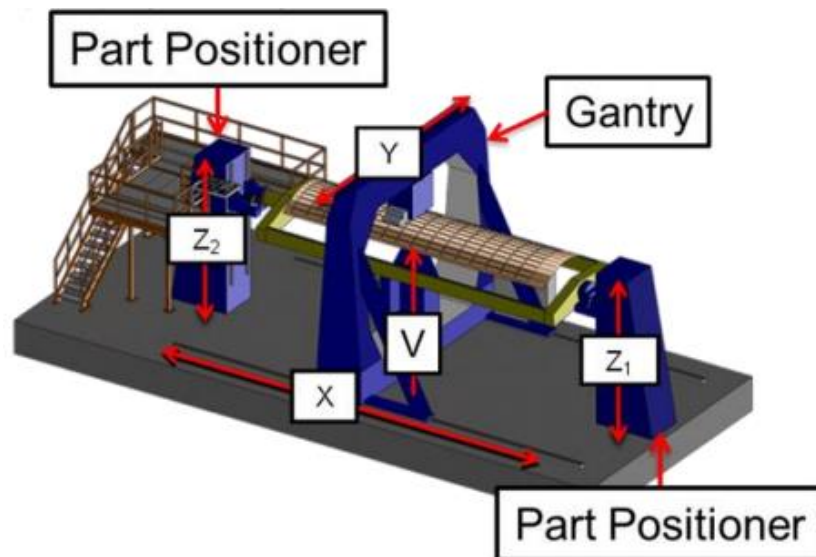


Figure 26 - Example of Machine and Aircraft Part models for computer process simulation (Nicholas Lum, 2014)

The programming/study offers a comprehensive analysis towards investigating the impact of operational parameters on the entire process. This provides the companies with indicators and guidelines (optimum path and parameters) for successful implementation of an effective operation (Chandran S. & Mathews J., 2016). The work channelization from generation to optimization also takes into account the different choices of operating variables and its likely impact on the surface. A sound prior knowledge on these factors will put the company in competitive advantage.

2.11 Maintenance 4.0

The new industrial revolution has begun. Manufacturing industries are focusing on digitization, production and development of manufacturing technologies (Gunther Reinhart and Georg Wünsch, 2007). Recently, emerging technologies (e.g., Internet of Things (IoT), wireless sensor networks, big data, cloud computing, embedded system, and mobile Internet) are being introduced into the manufacturing environment. In the literature on production, the changes are referred to as the next industrial revolution, which is commonly called “Industry 4.0”. Figure 27 illustrates evolutions of Industry 4.0.

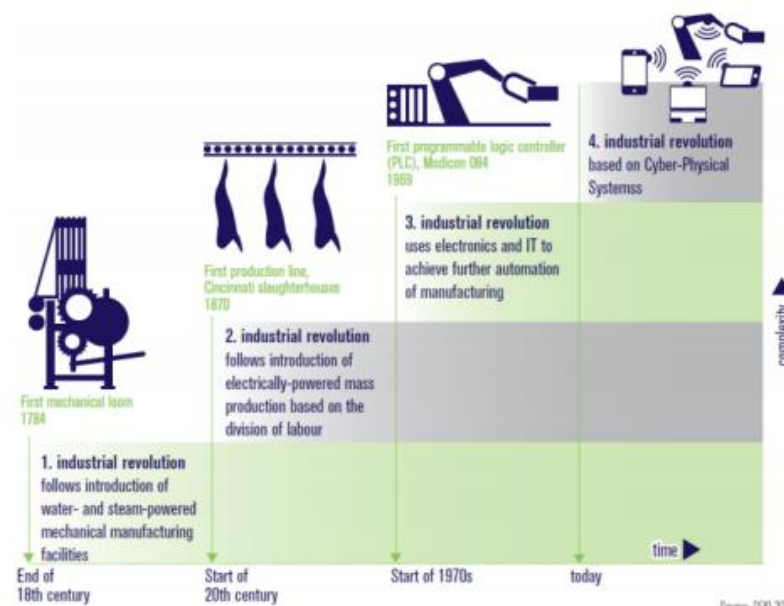


Figure 27 - The way of industrial revolution retrieved (German Research Centre for Intelligence, 2014)

A big cost of the production cost is the maintenance, which can be between 15 to 60 percent of the total production cost [Mobley, 2002]. To ensure production is running at a high efficiency and with minimum breakdowns, it is critical having the machine in good conditions and that maintenance is performed fast when required. This can be done by scheduling maintenance to change parts or repair worn out parts in the machines. Maintenance will always be required, and it is important to find the right timing to perform maintenance in the factory without disturbing the production, and at same time without compromising neighbour parts (Anton Alveflo & Christoffer Hildebrand, 2017). Some parts can be designed for a few thousand hours and some are designed for a specific number of starts and stops (Sullivan et al., 2004).

It is not possible to look for solutions without considering technology as an integral component of the development. Regarding the application of new technologies in machines and devices we use today, the most common term used is “smart machine”.

This implies a machine that is better connected, more flexible, more efficient, and safer. It can quickly respond to new demands. A Smart Machine has three main components: physical components, smart components, and connectivity components. Smart components are directly connected with services related to the physical parts, while connectivity allows exchanging information between the machine and its environment and enables services to exist outside the physical machine itself (Monostori et al., 2016).

Information gathered through real-time data from machines can contribute to the production line by optimizing scheduled maintenance event and thereby reducing unplanned failures (Roy et al., 2016), maintenance can then be performed when suited. The condition of machines, tools and equipment can be monitored with sensors such as vibration detectors, tachometers, temperature sensors, servo motors torque and energy consumption, etc. these measurements are performed continuously (online) or periodically. The key is to get the right information at the right time, allowing the system to schedule maintenance at the most cost-effective point: to prevent unexpected equipment failures and only maintaining equipment when needed. Below at Figure 28 is an illustration of the information flow. The equipment will then be maintained as few times as possible to keep costs down (Anton Alveflo & Christoffer Hildebrand, 2017).

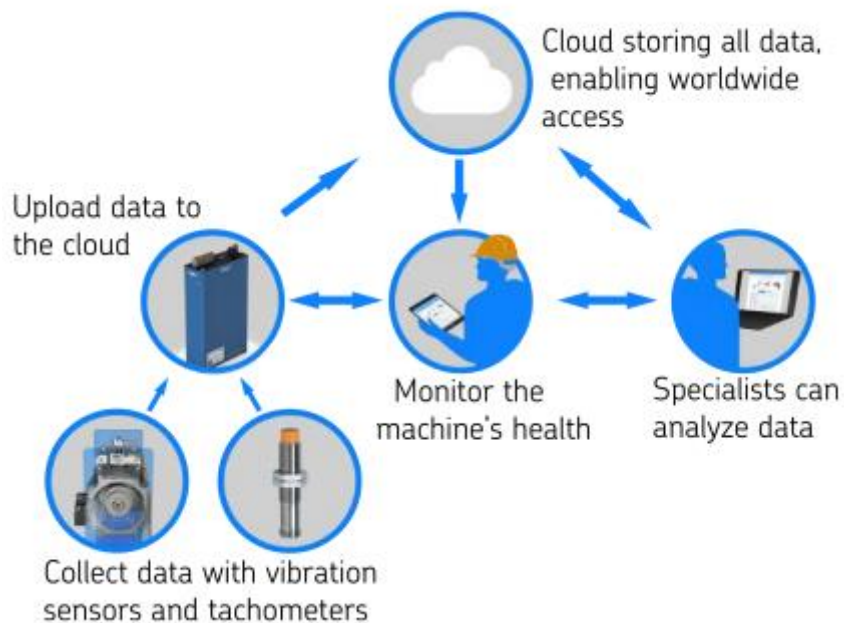


Figure 28 - Illustration of information flow (Anton Alveflo & Christoffer Hildebrand, 2017)

Maintenance is often introduced after production facilities are completely done. Design for Maintenance is used to evaluate maintenance issues in the concept phase and eliminate them if necessary. Sometimes tools like FMEA are used during the design phase, to evaluate the impact of certain components or behaviours of the machine. Maintenance requirements necessary for certain components can be very costly and

add up to a great amount of what the component cost. This is usually not included in the design [Liu and R.A. Issa, 2014]. Reliability and maintainability are two increasingly growing vital factors in maintenance solutions (Okogbaa and Otieno, 2015). To increase the performance and reduce the cost of the systems, the probability of failures has to be minimized and the ability to bring systems back after unavoidable failures increases (Okogbaa and Otieno, 2015). Machines that are designed for productivity but does not take maintainability into consideration may not be productive or economically defensible in the long run, because although the machine can actually work at high rates, the high down time for maintenance would drop this efficiency. Machines that are easy to maintain are more likely to get the required standards of maintenance (Desai and Mital, 2006). Changes in the design can be important when maintaining the production system. This is preferably designed to have a high maintainability so it can be repaired quickly (Vaneker and van Diepen, 2016). Common sense is often used when designing for maintenance. Changing the design in an early stage is often cheaper than making temporally changes and improvements when the production is running.

DEVELOPMENT

3 DEVELOPMENT

3.1 Company Overview

Electroimpact's CEO, Peter Zieve, has given me the opportunity to analyse one of their bestselling machines, and come up with a proposal for rate increase, as well as a hand full of new ideas for processes optimizations, along with other organizational ideas for improving the customer's efficiency and cost savings.

"Electroimpact is a highly experienced aerospace automation company with an exceptional concentration of engineers. Our wide range of projects include complete automation assembly systems for commercial aircraft wings, riveting machines and tools for wing panel and fuselage assembly, advanced fiber placement machines, robotic assembly systems, and spacecraft handling equipment. Our company was designed by the founder as a haven for engineers, with vertical responsibility for all work from concept to customer acceptance with minimal bureaucracy and barriers to success. Figure 29, is an overview of the campus in US.

U.S. Facilities - [Campus Map](#)

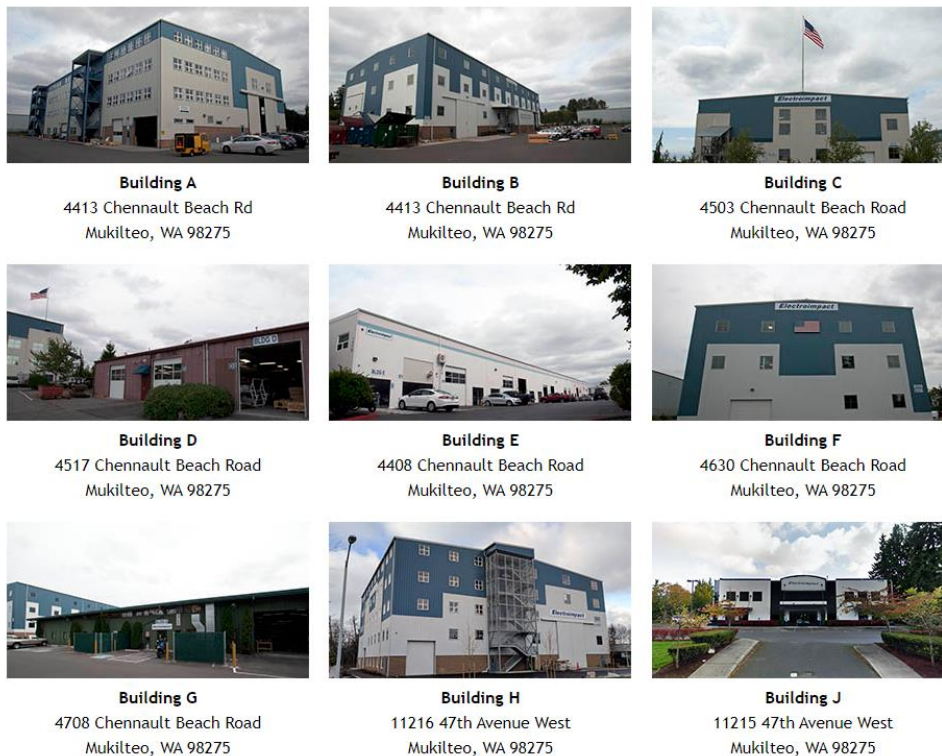


Figure 29 – Electroimpact campus (USA)

This unique approach has resulted in Electroimpact growing to become the largest integrator of aircraft assembly lines in the world. Our customer base includes Airbus, Boeing, Kawasaki Heavy Industries, Mitsubishi Heavy Industries, Spirit Aerospace, Vought, Northrop-Grumman, Israeli Aircraft Industries, Xi'an Aircraft of China, Bombardier, and Embraer, among others. Electroimpact is as well-versed in smaller product solutions as we are in some of the largest tooling jobs in the world.

Electroimpact's mission is to be the premier supplier of automated equipment to the worldwide aircraft industry. To do this, we will hire the best people and remove all barriers which would prevent them from doing the best job they can."

During this part of the project, data from a full production panel will be analysed in order to identify the weaknesses of the process and evaluate for each situation the best way to improve production efficiency and achieve consistent quality.

This work will be focused on the times when the machine has stopped for longer and where the non-machine-related operations directly affect production, causing delays. It is not possible to evaluate every single line due to scale. But it is not necessary once we are focusing on the critical tasks.

Note that this production data has come straight from the machine, so we are a 100% sure the logged events have happened. We are going to try to understand why and how to avoid, or how to resolve the events in a proper and quick way.

Besides the normal machine production data this work will focus on specific actions that can be considered to optimize the machine production rate, consumables, reduce the down time, product quality, and process cost reductions:

- 3.1 Production Planning;
- 3.2 Machine Production Data;
- 3.3 OEE Implementation;
- 3.4 Actions to Improve the Industrial Management of the Production Line
 - 3.4.1 Human Resources and Training
 - 3.4.2 Machine Time vs Operator Time
 - 3.4.3 Process Capability
 - 3.4.4 Logistics
 - 3.4.5 Maintenance 4.0
 - 3.4.6 Study of Times and Methods

It is Electroimpact's goal that each customer should be free to create new programs and studies using this machine's data. Improvements made by Electroimpact to a legacy

machine in production are also pulled into the source material used to develop following generations in a method of continuous improvement. The result is a more efficient machine is developed generations by generation.

3.2 Production Planning

The current planning strategies of most of the customers focus on continuous production making the maximum possible utilisation of the machines. There is a two-stage planning process where at the first level, the planning department decides which products and in what quantity they need to be produced. Their goal is primarily to satisfy their own customers. Their plan ensures the machines are employed to the maximum extent by matching the rate of parts to be produced with the capacity of the machines. At this level the core requirements are calculated and the order to start production is dispatched to the core shop .

The next level of planning is done by Production control which makes daily production plans. Their criteria is to make sure that the correct quantity of sub-parts, sub-assemblies and consumables are ordered so that the machines are completely utilised.

In simple terms, the first level complies with the market demand while the secondary plan with suppliers, logistics, stock management, and other variables: most of the time harder to control. This sometimes leads to a conflict of objectives between the two departments.

A good production planning system will integrate all the data necessary for production into a single platform for ease of access, will suggest possible products that could be added within schedule, will facilitate generating a weekly production plan before it is forwarded over to the next phase of the production, will automate production tasks and decisions as far as possible, facilitating strategic decisions to be taken by the engineers in charge. The system will not be completely automatic.

Below in Figure 30, is an SAP page, similar of what it is used by our customers.

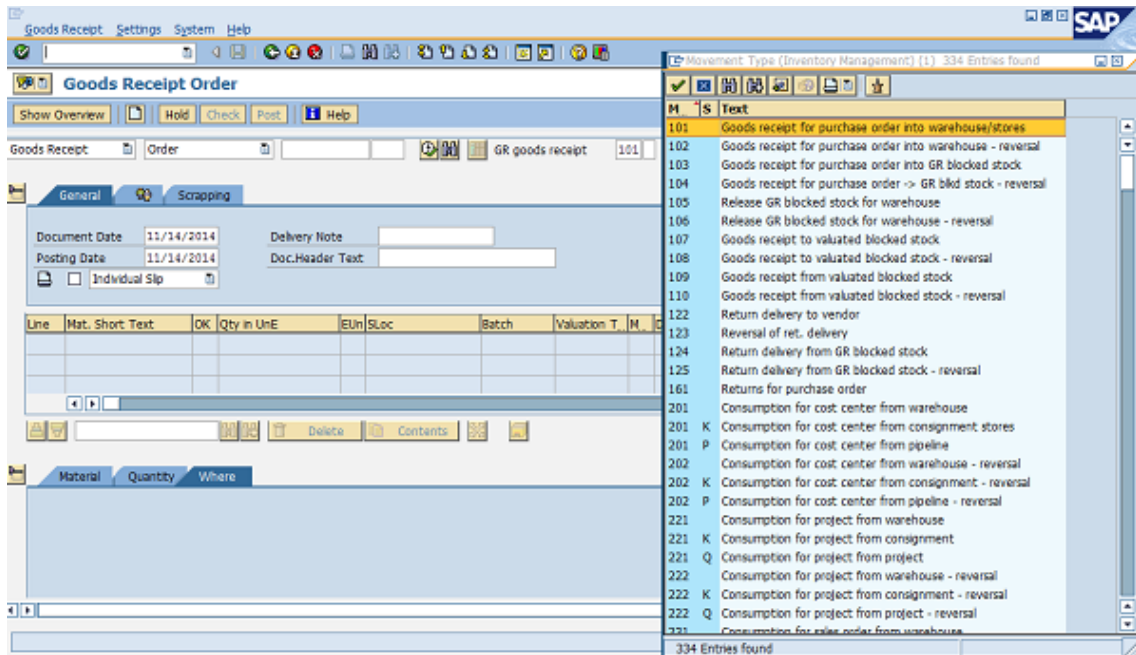


Figure 30 - SAP logistic management

The job of the planning team becomes more and more challenging as the rates increase, and the machine becomes busier.

3.3 Machine Production Data

Every single operation is recorded by the machine and stored for further analysis. Table 1, 2 and 3 below, show all of the parameters recorded by the machine.

Date, Time	Recorded from each operation as it starts
Duration of the cycle	Calculated as the difference between one operation and the next and added later, so we have a better visualization of the duration of each action, and this is where we first look to find outlying values
ProgramName	Name of the program the machine was running
ProgrammedX, Y, Z, A, B, C, U	This is the position of each vector, relative to an axis. X Y, Z, A, B, C, U;

Table 1 - Machine Data

Date	Time	Duration of cycle time	ProgramName	ProgrammedX
30/10/2019	12:37:01		//DATA_SV/O21070805.cnc	-7148.826
30/10/2019	12:38:44	00:01:43	//DATA_SV/O21070805.cnc	-7120.653
30/10/2019	13:45:54	01:07:10	//DATA_SV/O21070805.cnc	-7176.997
30/10/2019	13:47:26	00:01:32	//DATA_SV/O21070805.cnc	-7205.167
30/10/2019	13:47:32	00:00:06	//DATA_SV/O21070805.cnc	-7233.337
30/10/2019	13:47:39	00:00:07	//DATA_SV/O21070805.cnc	-7261.505
30/10/2019	13:47:47	00:00:08	//DATA_SV/O21070805.cnc	-7289.672
30/10/2019	13:47:54	00:00:07	//DATA_SV/O21070805.cnc	-7317.839
30/10/2019	13:48:05	00:00:11	//DATA_SV/O21070805.cnc	-7346.004

Table 2 - Program data (columns 1 to 5)

ProgrammedY	ProgrammedZ	ProgrammedA	ProgrammedB	ProgrammedC	ProgrammedU
2018.178	214.717	3.837	1.353	-4.011	40
2016.318	213.939	3.766	1.308	-4.028	40
2020.047	215.52	3.907	1.398	-4.028	40
2021.922	216.347	3.978	1.442	-4.044	40
2023.802	217.199	4.048	1.486	-4.061	40
2025.688	218.075	4.119	1.531	-4.078	40
2027.58	218.976	4.189	1.575	-4.093	40
2029.477	219.902	4.259	1.619	-4.111	40
2031.38	220.851	4.329	1.663	-4.135	40

Table 3 - Program data (columns 6 to 11)

This information obtained from the machine at every product, which includes many more columns and thousands of lines, are attached to this project.

A selection of times, that are out of the normal range, is going to be properly selected, in order to find the worst-case scenarios lived by the operators, and each of them will be analysed. We will discard the ones that relate to overnight stoppage, lunch, and other big numbers where we don't see any machine messages.

In the next chapter it will be given a proposal on how to improve each one of them, and how to improve the general process.

3.4 OEE Implementation

The OEE or *Overall Equipment Effectiveness*, considers the most common causes of lost productivity and turns them into a consistent metric that can be used to monitor and improve the production process.

The OEE is calculated based on the following formula:

$$\mathbf{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality}$$

Equation 7 - Formula for OEE (Michael O'Neill, 2012)

where,

$$\mathbf{Availability} = \text{Run Time} / \text{Planned Production Time}$$

Equation 8 – Formula for Availability (Michael O'Neill, 2012)

$$\mathbf{Quality} = \text{Total Count Quality Holes} / \text{Total Count}$$

Equation 9 - Formula for Quality (Michael O'Neill, 2012)

$$\mathbf{Performance} = (\text{Ideal Cycle Time} \times \text{Total Count}) / \text{Run Time}$$

Equation 10 - Formula for Performance (Michael O'Neill, 2012)

This performance indicator is particularly interesting for the process running on these machines because the data needed for it can be automatically provided by the machine. With the addition of a program created to collect and analyse the data from each machine an OEE system can be deployed that displays OEE to a user in real time, giving a clear and effective overview of production.

With the data, a production engineer can decide to either make an intervention or not. The values for an acceptable OEE need to be defined by the customer. It was learnt that values above 85% are generally good. But due to the complexity of the parts and processes the value on any given machine may differ.

The OEE is the start point for further process improvements. Depending on the factor that scores lowest, several parameters can be analysed. Looking at the data from the production log, engineers can analyse amongst other issues:

- Losses caused by non-planned stoppages.
- Losses due to machine not operating at its maximum speed.

- Machine breakdowns.
- Setup and calibrations.
- Specific stops.
- Start-up issues.
- Etc.

The first proposal is that companies prioritise the implementation of the OEE evaluation. Moving forward, we will understand the OEE is very low, due to the info we will analyse next.

3.5 PROPOSED ACTIONS TO IMPROVE THE INDUSTRIAL MANAGEMENT OF THE PRODUCTION AND THE MACHINE

Attached to this project is a document (with data from a wing panel production) in a machine belonging to an Electroimpact customer.

By analysis of the calculated operation duration using the attached production tables the author has selected some operations of interest.

3.5.1 Human Resources and Training

To give a little bit of context here, Electroimpact engineers have spent thousands of hours writing code and improving the processes, so the machine could be as fast as possible. They manage to get cycle times optimized to the best of the company knowledge and experience. As we stand, this machine can do a Rivet cycle time of 6.9 seconds, a Bolt cycle of 8.5 seconds, and a probe cycle of 11 second. As stated on the first part of this project, rivet and bolt cycle include normalization to the aircraft part, drilling, sealant, bolt/rivet insert, and rivet jamming or collar insert, depending of the bolt. This is true for a program that was tested and approved, and running in automatic mode, full speed.

At line 561 there is a long duration for a single operation (2'36"). There are three outcome messages from the machine (MSG474 MSG475 MSG114). Those relate respectively to Y tracer and V tracer out of position, and a detection of an aborted cycle.

This sequence of messages is likely occur when a program is shifted forward or a bolt location is deliberately avoided. There are in fact several reasons why an operator might

want to do this; the main requirements after a stop like this is to restart the program at the right place and put the machine into the correct state. This is what the operator has likely done, taking them over two and half minutes to achieve.

In general, the cycle times all along the program take more time than necessary. Sometimes over twice the normal cycle time.

It was noticed that operators usually use the manual functions; using the pendant to control the speed of the machine, ready to abort any process they think is not running as it should.

If a program was run already several times with no issues, then the machine will repeat the same exact movements repeatedly.

It was observed that operators are not comfortable with this complex machine. This led them to spend longer troubleshooting the error messages or being uncomfortable to run machine at full speed.

There are key factors, that were observed with time, at the route of this inexperience, fear, and lack of competence.

First, the selection of the operator needs to be made carefully: matching the profile of this person to the job required of them. Then, initial and continuous training is essential. This is not happening in the case study. It is vital to provide the operator with a good work environment and supply all the necessary tools for them to perform their job at their best.

Secondly, and not less important, the rotation on this job needs to be as little as possible. When a company invests a lot of resources training people, it needs to realise the gains of that investment. Rotating people to other factory sectors is not good practice.

3.5.2 Machine time vs operator time

At line 42 we see a 10 min stopping time. There is no error message, or anything anormal with the code from the machine. We have similar events on lines 75, 385, 391, 396, 399, 407, 409, etc. Within a production period of just under 5 hours the machine is stopped for more than 2 hours, with no apparent reason.

Based on what is known about this specific environment a few reasons can be proposed: a stop for a bathroom trip, a meeting, lunch, a conversation with a colleague, a quick maintenance of a tool, and so on.

Unfortunately, this is a common occurrence, but it is a bad habit which should be addressed. As explained during the first part of this thesis, the operator has quite a few

tasks to perform while the machine is in production. In parallel the operator must take care of a log, along with all the main actions of the day.

Assuming an average cost of the machine of 11 million Euros, at a 20 years investment and 7 day work week (standard for this type of company and aircraft), we arrive at a cost of 1506 €/day. An operator gets paid an average of 900€ a month, and assuming the company has to spend twice that amount per month including overheads (giving a total of 1800€). This means an operator costs 82€ per shift. Working 3 shifts, 246 €/day.

At current rate, a machine operating 3 shifts per day completes a panel every 3.5 days (10.5 shifts).

The proposal that comes from this is that customer should have not one, but two operators at all time. While one operator runs the machine, the second one is feeding the machine with the collars and bolts, cleaning the anvils, performing standard maintenance on the tools, doing the necessary logistic work to guarantee they never run short on supplies, etc. It is also intended that this second operator covers those necessary breaks from those mentioned before such as meetings, lunch, and other events, that they should not attend at the same time. Also, it would be a second person to troubleshoot the issues that may arise.

With two operators, the machine would be able to produce 1 panel every 2.7 days (8 shifts).

The production costs would increase from 1756 €/day (machine + 1 operator), up to 2002 €/day, or a 14% increase in production costs.

The production rates would go from 8.5 panels per month up to 11.1 panels per month, an increase of 30%.

Those are very conservative numbers which would be realised at an early stage. I believe this can go beyond 30%. As the operators become more experienced and better trained, the number of panels produced per month can increase.

NOTE: this two operator scheme only applies when production rate is more than 8 panels per month, and with three shifts per day.

3.5.3 Process Capability – Control charts

Production report, line 708, (MSG303 MSG303 MSG303 MSG303) - hole outside specific tolerance.

This is the reason the machine often stops for more than 30 minutes. The primary cause for this happening is that the drill is at end of life.

The solution could be as easy as following the manufacturer's instructions on the tool lifetime. However, this is not accurate and can vary each way (higher or lower lifetime).

Industrial management has a very interesting solution for this specific problem. Together with the manufacturer's technical documentation and the values provided by the probe it is possible to monitor each tool as it wears. This data can be utilised to better anticipate when a drill bit is going to get to reach end of life.

Variability of process is something every company wants to avoid at all costs. Good practices and best methods have been developed to try to bring stability to all processes. In this specific case, this is directly affected by the quality of the manufacturing of the drill, quality of the aluminium (AC part), and the capability of the process.

This is one of the proposals to increase the "Quality" factor within the OEE evaluation.

Process capability analysis answers the question of how well a process meets specification – either those set by a customer or internal specifications.

To calculate process capability, it is needed to be able to estimate the process average and the process standard deviation.

This is particularly interesting if the production team are keen to never stop the machine and at the same time reduce stock inventory. It is possible to anticipate the day when the drill bit is going to be removed from service and order a new one to be on site just before this happens. It also reduces the probability of a hole OOT, reducing the time machine is stopped, and reduced the costs that may come with the rework of a bad hole.

Below, on Figure 31, is a chart of Process Capability for the ¼" drill bit. Measurements are extracted from the production data. The probe measures one hole in ten drilled. This allows us to perform a simple study of the repeatability of the process. Note that a hole might not need to be OOT for the process be considered not capable.

As we can see on the control chart, although the process is no inside the upper and lower limits, it is in tolerance, being the Upper tolerance of 6.312mm and the Lower tolerance of 6.262mm.

The calculated Cpk for those 125 sample is 2.595. We are used to see numbers around 3.5 for Cpk on this process.

Quality Tools

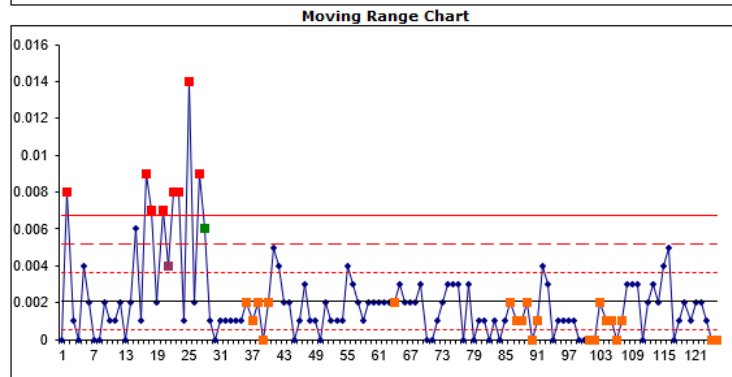
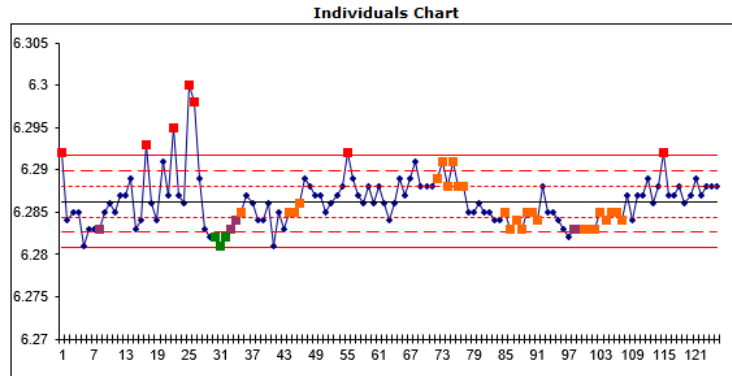
Control Charts

Description

This template illustrates a Statistical Process Control (SPC) chart.

Instructions

- Select the correct subgroup size. When in doubt, select a subgroup size of one. Partial subgroups are not displayed.
 - One Two Three
 - Four Five Six
- Enter up to 200 data points in the cells provided. Do not enter values in the subgroup column. These cells update automatically to show the subgroup in which the data point is included.
- Identify any out of control conditions. Four tests are performed. Use the legend to identify the points corresponding to a particular test.
- If a test looks for a proportion of points, only the offending point will be identified. For example, if eight points in a row are on one side of the centerline only the eighth point will be identified.



- Three Sigma Limit
- - - Two Sigma Limit
- - - One Sigma Limit
- Average
- A single point outside the control limits
- Two of three pts outside the two sigma limit
- Four of five pts outside the one sigma limit
- Eight in a row on the same side of centerline

Control Chart Data

6.2862 Xbar/IMR Chart Avg	6.288 Xbar one sigma Upper Limit	0.004 Rbar one sigma Upper Limit
0.002 Range Chart Avg	6.29 Xbar two sigma Upper Limit	0.005 Rbar two sigma Upper Limit
0.001816 Rbar/d ₂	6.292 Xbar three sigma Upper Limit	0.007 Rbar three sigma Upper Limit
125 Number of samples	6.284 Xbar one sigma Lower Limit	5E-04 Rbar one sigma Lower Limit
1 Subgroup size	6.283 Xbar two sigma Lower Limit	n/a Rbar two sigma Lower Limit
125 Number of subgroups	6.281 Xbar three sigma Lower Limit	n/a Rbar three sigma Lower Limit

Sub Group	Data	Sub Group	Data	Sub Group	Data	Sub Group	Data	Sub Group	Data	Sub Group	Data	Sub Group	Data	Sub Group	Data
1	6.292	26	6.298	51	6.285	76	6.288	101	6.283	126		151		176	
2	6.284	27	6.289	52	6.286	77	6.288	102	6.283	127		152		177	
3	6.285	28	6.283	53	6.287	78	6.285	103	6.285	128		153		178	
4	6.285	29	6.282	54	6.288	79	6.285	104	6.284	129		154		179	
5	6.281	30	6.282	55	6.292	80	6.286	105	6.285	130		155		180	
6	6.283	31	6.281	56	6.289	81	6.285	106	6.285	131		156		181	
7	6.283	32	6.282	57	6.287	82	6.285	107	6.284	132		157		182	
8	6.283	33	6.283	58	6.286	83	6.284	108	6.287	133		158		183	
9	6.285	34	6.284	59	6.288	84	6.284	109	6.284	134		159		184	
10	6.286	35	6.285	60	6.286	85	6.285	110	6.287	135		160		185	
11	6.285	36	6.287	61	6.288	86	6.283	111	6.287	136		161		186	
12	6.287	37	6.286	62	6.286	87	6.284	112	6.289	137		162		187	
13	6.287	38	6.284	63	6.284	88	6.283	113	6.286	138		163		188	
14	6.289	39	6.284	64	6.286	89	6.285	114	6.288	139		164		189	
15	6.283	40	6.286	65	6.289	90	6.285	115	6.292	140		165		190	
16	6.284	41	6.281	66	6.287	91	6.284	116	6.287	141		166		191	
17	6.293	42	6.285	67	6.289	92	6.288	117	6.287	142		167		192	
18	6.286	43	6.283	68	6.291	93	6.285	118	6.288	143		168		193	
19	6.284	44	6.285	69	6.288	94	6.285	119	6.286	144		169		194	
20	6.291	45	6.285	70	6.288	95	6.284	120	6.287	145		170		195	
21	6.287	46	6.286	71	6.288	96	6.283	121	6.289	146		171		196	
22	6.295	47	6.289	72	6.289	97	6.282	122	6.287	147		172		197	
23	6.287	48	6.288	73	6.291	98	6.283	123	6.288	148		173		198	
24	6.286	49	6.287	74	6.288	99	6.283	124	6.288	149		174		199	
25	6.3	50	6.287	75	6.291	100	6.283	125	6.288	150		175		200	

Figure 31 - Control Chart

3.5.4 Logistics

There are a considerable number of times that people walk in and out of the machine area, which is surrounded by a fence.

Many times this is in order to bring goods in to refill the machine consumables shelves. There is efficiency to be gained here, regarding the supplies. Not just by management of when people are permitted to enter (this needs to be avoided as much as possible), but also to wisely use the time people spend on the line. It is key that when an operator refills a machine, this is thought all way through. An empty shelf of a specific type of fastener doesn't automatically need a refill or even a purchase order put in place. For example, sometimes a specific fastener size won't be used for another week or two. So when operators bring new consumables to the machine, those parts should be required in the next few programs to be run. A list of required parts can be generated automatically when the machine programs are chosen for the day.

Being on the production line for so long it was easy to notice the number of times the machine stopped waiting for bolts, rivets, collars, etc. On the other hand, it is possible to see shelves with specific sizes completely full for weeks. Of course, each customer has their own way to order the supplies as each one negotiates the quantities in their own way. It is hard to suggest a winning strategy: keeping stock, or just in time ordering. What Electroimpact machines can do is giving precise information of future demand.

The information generated by the machine will answer three important questions to the logistics team:

- When to order?
- How much to order?
- How much shall the security stock be?

It is then possible to follow an efficient stock management process. This will reduce costs to the company at the three critical stages:

- Provisioning costs
- Costs associated with the storage and handling of stocks
- Costs associated with stock running out

It is particularly easy to do this management here, where the range of products on the machine is very small, and where planning can determine quite accurately what goes on the machine and when. This is true for the current production rate or for the most optimized production rate. Either way, the company has enough records to calculate this accurately. The more efficient the machine is the more optimized this stock management can be.

A Kanban system would not be very effective here: just because a specific shelf is empty, this doesn't mean more need to be ordered. Or the opposite way around: the high demand sized rivets and bolts can never be allowed to run out since this would automatically trigger a production stop.

Looking at the monthly demands, assuming production is properly planned, each customer can calculate the best way to manage the stock as explained above.

It would be interesting to see people filling the shelves from the outside without having to access the interior of the production line. Operators could then reach them without leaving the cell. In this specific task a Kanban style system would work fine.

3.5.5 Maintenance 4.0

Recent research has been interested in how maintenance interacts with manufacturing and how it contributes to high performance organisations. It shows that preventive and company-wide integrated maintenance is important for companies seeking process control and flexibility; and is critical for high performance in high-tech companies. Based on empirical analysis it is hypothesised that for highest performance, companies should simultaneously emphasise soft and hard issues of maintenance and preventive maintenance, respectively. Integration of maintenance knowledge into cross-functional design teams, the OEE measure into the overall manufacturing performance measurement system, and maintenance planning into manufacturing planning and control systems are other aspects that most likely lead to improved performance in the average company.

Industry 4.0 can be applied to this machine which contains more than 100 servo motors, pneumatic actuators, sensors, and many other mechanical components that require preventive maintenance. There are software solutions that can remind the team of the next planned maintenance. But this date can vary a lot, depending on the production rate actually planned on the machine. One of the advantages of Industry 4.0 technology is that it makes it possible to track most of the electronic components, and even some mechanical components, and alert the maintenance team when it is time to replace a component, or if something abnormal is happening. Figure 32, is a picture representation of the Industry 4.0 chain of events.

In this way it is possible for production and maintenance to work side by side, utilising real time information. It is possible to plan a routine maintenance, or even a curative one, with hours or days advance notice. For example, a servo motor can provide enough information to the system to allow an engineer or system to interpret that information and generate a possible action. On other items (e.g. sensors of pneumatic actuators) there is a lifetime expressed as a number of cycles given by the manufacturer. This can be recorded by the machine and a warning can be generated in order to replace those items. The main goal is to replace each item at the right time, not before (would increase the cost of the spares and maintenance), and not after (which can cause other problems with adjacent components, or can even affect the quality of the process).

Similarly to the Cpk study on consumables, Industry 4.0 principals will allow the customer to reduce their stock of spares to a minimum; once it can be determined in advance which components to replace and order them just in time for the planned maintenance. On Figure 33, it is illustrated the three horizons of Industry 4.0.

Three horizons of Industry 4.0 implementation and usage

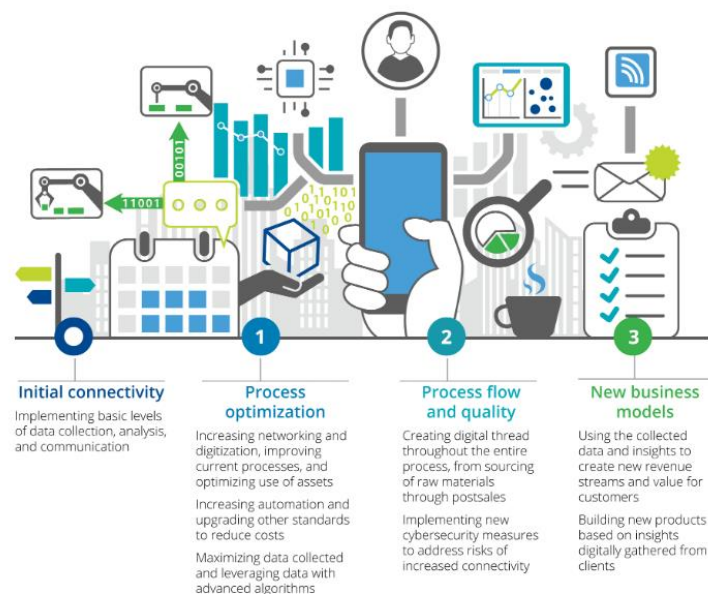


Figure 322 - Three horizons Industry 4.0 - Eli Tidhar, Jeremy Siegman, Dan Paikowsky, 2019

This is a complement to the “Availability” variable on the OEE. As this work stated before; the main cost of the production is the daily cost of the machine. The less time it spends stopped, the more return it brings to the owner.

3.5.6 Computer simulation

Computer simulation is a method to build computer model of a real-world industrial problem. Simulation software is used to build the rules and behaviour mechanisms to play the game and then to run the model on a certain time. The key feature of simulation is that it is possible to conduct tests on a virtual world that would not be possible in the real world without large damage.

On Figure 34, is a comparison between virtual and physical machine.

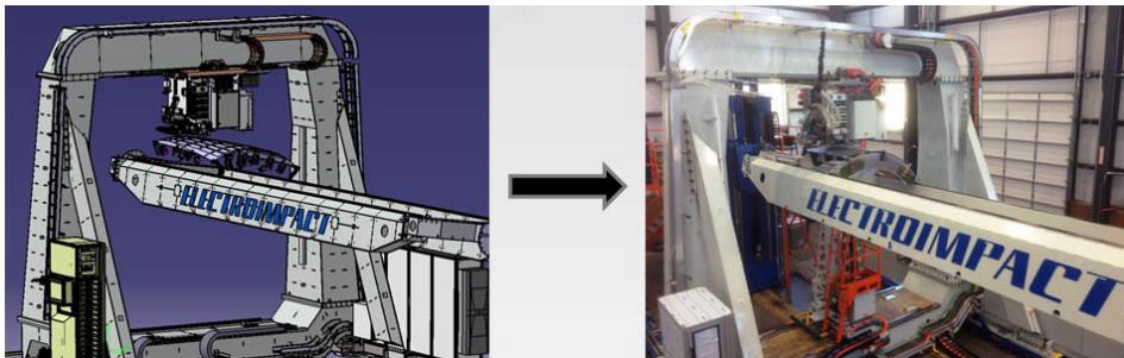


Figure 33 - CAD vs Real Machine

The main convergence between NC Programming and production rates or/program run times is on how much machine movement there is. The cycle times (resyncing, drilling, etc) are not under NC programmer control, but they can control how much the machine moves back and forth across the part. A well-designed programming plan can mitigate this, reducing machine movements and hopefully negating the need for re-work later on to reduce program run times. There is improvement to be added after a program is run a few times by analysing how much time is taken up by machine movements and trying to minimize those.

An important part of this is to have the NC Programmer better integrated into the manufacturing process, not just stuck in a room staring at a computer screen. If they can see the machine and programs running in real life it helps them to see what the process is really like and where improvements can be made.

There are a number of simulation solutions it is possible to do this with for offline programming. It is possible to determine with a high accuracy answers to many questions, for example:

- What is the expected capacity of the factory?

- How will the supply chain behave at extremely high rates?
- What is the investment payback time for a production system upgrade?
- What is the time saving of an improvement?
- In which order should programs be run to make the most efficient use of resources?
- What stock must exist prior to each program being run?
- What is the optimal path of each program?
- What tools must be ready before the next program starts?
- What tasks shall operator perform in each single step of production?
- What messages shall be sent to engineering team or logistics team at each step?

Figure 35, illustrates the tree, of the CATIA environment.

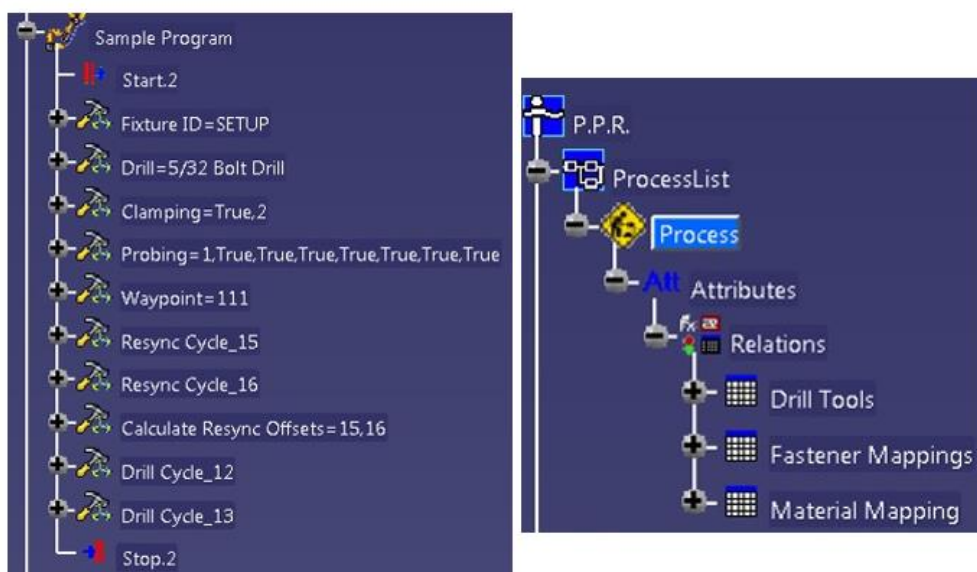


Figure 34 - Tree visualization in CATIA

Offline programming and simulation also supports some quality inspection tasks like:

- Verification of model – does the model work as intended?
- Walk-through, animations, testing.
- Quantity of fasteners installed.
- Does the result match with actual with the same initial conditions?

Figure 36 shows a real time simulation:

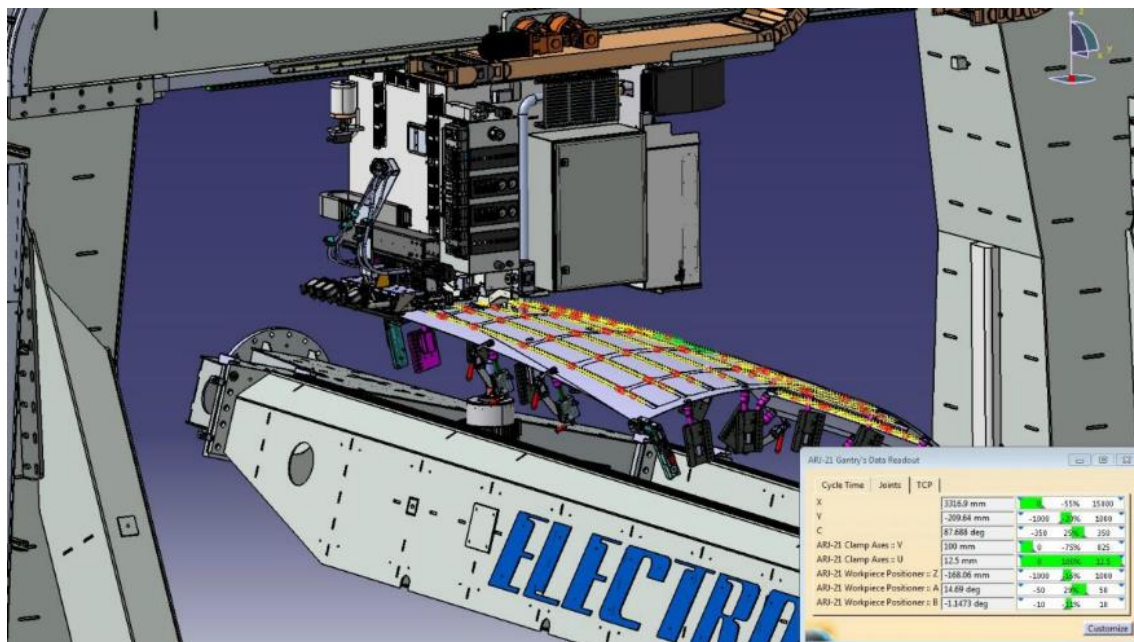


Figure 335 - Simulation

It is possible to see the high quality of the simulation, once it is very similar to the real machine and product. This is the best way to, offline, try all the possible case scenarios, and simulate all machine and AC part movements.

DISCUSSION OF RESULTS & CONCLUSIONS

4 DISCUSSION OF RESULTS AND CONCLUSIONS

In this project a careful examination of the available data and of the onsite work was undertaken. There were many factors involved to justify the current production rates and this thesis evaluated some of them.

With high demands, new ways of work are invented, defined and implemented. It is always good when we can do more with the same. And this is kind of an inverted exponential curve. Some of Electroimpact customers still are at a high position of the curve. From the example program we analysed there are many conclusions and proposals for improvements that can be made by this customer. There is a great potential for production increase.

The focus is on how to ensure that the machine is always running and that's why every major stoppage was analysed. There are other stoppages we can't determine accurately from this program log, and which would require that we sit next to the machine for every single minute. That has to be an ongoing effort. This unfortunately is a limitation of this work, along with a refusal to calculate the OEE from the customers which would give a starting point value.

From the data, it is possible to see that one operator is not enough for this highly complex machine, with so many features and a high demand of goods, so there is a proposal made of an addition of a second operator. It is shown that the additional costs of operations are largely compensated by the production increase.

Because of this high demand of goods it is necessary to have a very dynamic logistic department working towards supplying the machine efficiently. Supplying the machine might not be too difficult; but do it in a way where there is a balance of the stocks levels, that can be more challenging. It is necessary to supply the machine without interfering with production. This could be done with Kanban shelves, or a similar system, integrated into the barrier to the production cell.

Maintenance can play a key factor on this machine. With so many components, it is important to attend to all the programmed maintenance and be quick to react when something fails. If we can understand when something is about to fail and intervene before it happens, then we would be thinking in a maintenance 4.0 way. This brings great advantages at many levels. This machine has highly complex parts and mechanisms that communicate with the machine at all times, generating many and important data. These data should be used to the customer's benefit.

Well-planned NC programming, where the sequence of the programs is carefully chosen to avoid wasting time, can also increase efficiency. Unfortunately, there was not enough

time to deeper into this. There are many programs to analyse which need careful control of times and movements.

By improving training for operators, engineers, and techs, customers can get more from their human resources.

New and customised programs could be added to this machine, that can support many different kinds of new features. As demonstrated in this work, it is possible to implement some studies that are favoured in the automotive industries which are used to working at demanding high rates, such as Cpk.

Customers have probably a bigger list of processes that they want to improve, and specific problems to be solved. We didn't have access to that, but if each one is analysed individually, it is probably possible to find or create a solution, within the capacities of the machine.

For this specific customer it is clearly possible to increase the rates by at least 30 to 45% depending on what proposals are implemented, and how they are implemented. The main factor that will determine how much can of an increase will be realised is the rate demanded. For this specific customer, there is not yet demand for enough panels to keep the machine running 100% of the time, but they will very soon be on the other side of the coin.

It is in Electroimpact's best interests to get the fastest and best machines on the market, and this is proven in production. The faster a machine outputs, the more products there are to split its own cost across, and therefore the cheaper it will be for customer in the long term. And this, in the very end, influences the price of the airplanes.

**BIBLIOGRAPHY AND OTHER
SOURCES OF INFORMATION**

5 BIBLIOGRAPHY AND OTHER SOURCES OF INFORMATION

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APENDIX

6 APENDIX

6.1 APPENDIX 1 - SUPPLEMENTARY INFORMATION

APPENDIX: SUPPLEMENTARY INFORMATION

Appendix A: Specific cutting force

Specific cutting force (Sandvik, u.d.).

MC code	Material group	Material sub-group	Manufacturing process	Heat treatment	nom	Specific cutting force, k_{ct} (N/mm ²)	m_c	
N1.1.Z.UT	aluminium based alloys	1 commercially pure	Z	UT untreated	30 HB	350	0,25	
N1.2.Z.UT		2	Z cast	UT untreated	60 HB	400	0,25	
N1.2.Z.AG		2	Z	AG aged	100 HB	650	0,25	
N1.2.S.UT		2	S sintered	UT untreated	75 HB	410	0,25	
N1.2.C.NS		2	C	NS not specified	80 HB	410	0,25	
N1.3.C.UT		3	C cast	UT untreated	75 HB	600	0,25	
N1.3.C.AG		3	C cast	AG aged	90 HB	700	0,25	
N1.4.C.NS		4	C cast	NS not specified	130 HB	700	0,25	
N2.0.C.UT		magnesium based alloys	0 main group	C cast	UT untreated	70 HB		
N3.1.U.UT		copper based alloys	1 non-lead copper alloys (incl. electrolytic copper)	U not specified	UT untreated	100 HB	1350	0,25
N3.2C.UT	2 leaded brass & bronzes (Pb <1%)		C cast	UT untreated	90 HB	550	0,25	
N3.3.S.UT	2		S sintered	UT untreated	35 HB			
N3.3.U.UT	3 free cutting copper based alloys (Pb >1%)		U not specified	UT untreated	110 HB	550	0,25	
N3.4.C.UT	4 high strength bronzes (>225HB)		C cast	UT untreated	300 HB			
N4.0.C.UT	zinc based alloys	0 main group	C cast	UT untreated	70 HB			

MC code	Material group	Material sub-group	Manufacturing process	Heat treatment	nom	Specific cutting force, k_{ct} (N/mm ²)	m_c
S1.0.U.AN	iron based alloys	1 main group	U not specified	AN annealed	200 HB	2400	0,25
S1.0.U.AG		2	U not specified	AG aged	280 HB	2500	0,25
S2.0.Z.AN	nickel based alloys	0 main group	Z	AN annealed	250 HB	2650	0,25
S2.0.Z.AG		0	Z forged/rolled/cold drawn	AG aged	350 HB	2000	0,25
S2.0.Z.UT		0	Z	UT untreated	275 HB	2750	0,25
S2.0.C.NS		0	C cast	NS not specified	320 HB	3000	0,25
S3.0.Z.AN	cobalt based alloys	0 main group	Z forged/rolled/cold drawn	AN annealed	200 HB	2700	0,25
S3.0.Z.AG		0	Z forged/rolled/cold drawn	AG aged	300 HB	3000	0,25
S3.0.C.NS		0	C cast	NS not specified	320 HB	3100	0,25
S4.1.Z.UT	titanium based alloys	1 commercially pure (>99,5% Ti)	Z	UT untreated	200 HB	1300	0,23
S4.2.Z.AN		2 alpha and near alpha alloys	Z	AN annealed	320 HB	1400	
S4.3.Z.AN		3 alpha/beta alloys	Z forged/rolled/cold drawn	AN annealed	330 HB	1400	
S4.3.Z.AG		3	Z forged/rolled/cold drawn	AG aged	375 HB	1400	
S4.4.Z.AN		4 beta alloys	Z	AN annealed	330 HB	1400	
S4.4.Z.AG		4	Z	AG aged	410 HB	1400	
S5.0.U.NS	tungsten based	0 main group	U not specified	NS not specified	120 HB		
S6.0.U.NS	molybdenum based	0 main group	U not specified	NS not specified	200 HB		

Figure 34 - Appendix A

6.2 APENDIX 2 – MACHINE DATA

Following the data previously showed at this project, relative to machine production, in this attachment, more information follows relative to the next columns of information.

The machine then counts the cycles and the number of drilled holes. It is shown next the type of cycle ran and the feed rate. For each of the next columns, the number “1” means yes, and the number “0” means no. This refers to: Solid (AC part), Tack (if it is drilling a tack), Doubler, Upper and Lower all refer to type of AC panels.

Programme dV	CycleCou nt	DrillCou nt	CycleGCo de	FeedRa te	Soli d	Tac k	Doubl er	Upp er	Low er	VT P
15	706734	676917	166	10500	1	0	0	0	1	0
28.132	706735	676918	166	10500	1	0	0	0	1	0
15	706736	676919	166	10500	1	0	0	0	1	0
15	706737	676920	166	10500	1	0	0	0	1	0
15	706738	676921	166	10500	1	0	0	0	1	0
15	706739	676922	166	10500	1	0	0	0	1	0
15	706740	676923	166	10500	1	0	0	0	1	0
15	706741	676924	166	10500	1	0	0	0	1	0
15	706742	676925	166	10500	1	0	0	0	1	0

Table 4- Program data (columns 12 to 22)

Here, the first and second column identify the type of the AC. Cycle Inhibit column refers to if the operator is enabling each of the single operations, and the rest identifies the type of operation.

Ti- Mode	E2- Mode	CycleInhibit	ClampOnly	Cado	DrillOnly	CollarOnly	FastenerOnly
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0
0	1	0	0	0	1	0	0

Table 5 - Program data (columns 21 to 30)

Next it is shown the number of the tool, and anvil, nose piece, squeeze mode, what spindle is using, and the number of the block\line on the NC program. Program number

ToolNumber	Anvil	Nosepiece	SqueezeMode	Spindle1	Spindle2	BlockNum	ProgramNumber
8	15	2	Position	Active	Inactive	225	0
8	15	2	Position	Active	Inactive	240	0
8	15	2	Position	Active	Inactive	255	0
8	15	2	Position	Active	Inactive	260	0
8	15	2	Position	Active	Inactive	265	0
8	15	2	Position	Active	Inactive	270	0
8	15	2	Position	Active	Inactive	280	0
8	15	2	Position	Active	Inactive	285	0
8	15	2	Position	Active	Inactive	290	0

Table 6- Program data (columns 31 to 38)

Feed rate, and now the machine positions for each axis.

FeedRateOverride	MachineX	MachineYU	MachineYV	MachineAU	MachineAV	MachineBU
-	-	-	-	-	-	-
30	24942.289	836.27	1118.95	5.079	5.122	1.088
-	-	-	-	-	-	-
30	24915.735	835.741	1114.714	5.012	5.056	1.003
-	-	-	-	-	-	-
60	24969.179	837.108	1121.807	5.115	5.159	1.156
-	-	-	-	-	-	-
100	24995.978	837.662	1126.095	5.182	5.226	1.228
-	-	-	-	-	-	-
100	25022.788	838.444	1130.107	5.24	5.284	1.3
100	-25049.95	838.934	1134.536	5.311	5.355	1.354
-	-	-	-	-	-	-
100	25077.194	839.931	1138.257	5.36	5.404	1.403
-	-	-	-	-	-	-
100	25105.098	840.86	1142.148	5.413	5.457	1.418
-	-	-	-	-	-	-
100	25133.076	841.045	1147.181	5.5	5.544	1.428

Table 7- Program data (columns 39 to 45)

On the next table is shown the load on the ball screw, and on the HS, the measured stack, and the values read by each tracer and normality sensors.

VBallscrewLoad	HSLoad	MeasuredStack	VTracer	YTracer	Norm1	Norm2	Norm3	Norm4
685	685	13.363	15.081	11.425	40.194	39.786	39.786	40.169
721	676	13.509	14.662	11.225	40.199	39.788	39.85	40.234
685	681	13.289	15.036	11.449	40.199	39.812	39.846	40.21
685	681	13.163	15.008	11.37	40.189	39.814	39.85	40.217
690	681	13.056	15.012	11.337	40.186	39.865	39.818	40.159
690	681	12.924	14.966	11.376	40.167	39.818	39.825	40.17
703	681	12.81	15.035	11.451	40.194	39.818	39.782	40.167
699	681	12.703	15.038	11.449	40.199	39.814	39.798	40.161
694	681	12.601	15.025	11.464	40.196	39.817	39.794	40.213

Table 8- Program data (columns 46 to 54)

Follows the length of the tool, the measurement of the tool, diameter, dimensions if the tip of the tool, countersunk, gauge and countersunk offset.

ToolLengthOnChip	MeasuredLength	Diameter	TipLength	NominalCsk	GaugeLength	CSKOffset
134.43	134.379	4.762	0.98	1.17	117.329	0.061
134.43	134.379	4.762	0.98	1.17	117.329	0.061
134.43	134.379	4.762	0.98	1.17	117.329	0.051
134.43	134.379	4.762	0.98	1.17	117.329	0.051
134.43	134.379	4.762	0.98	1.17	117.329	0.051
134.43	134.379	4.762	0.98	1.17	117.329	0.051
134.43	134.379	4.762	0.98	1.17	117.329	0.051
134.43	134.379	4.762	0.98	1.17	117.329	0.051
134.43	134.379	4.762	0.98	1.17	117.329	0.051
134.43	134.379	4.762	0.98	1.17	117.329	0.051

Table 9- Program data (columns 55 to 61)

Number of cycles, max and min diameter read, max and min countersink read, how deep the countersink is;

ToolLife	MaxDiameter	MinDiameter	MaxCs	MinCs	MinBreakthrough	PeckCutof	PeckIncrement
3607	4.788	4.738	0.1	-0.06	1.48	5	20
3608	4.788	4.738	0.1	-0.06	1.48	5	20
3609	4.788	4.738	0.1	-0.06	1.48	5	20
3610	4.788	4.738	0.1	-0.06	1.48	5	20
3611	4.788	4.738	0.1	-0.06	1.48	5	20
3612	4.788	4.738	0.1	-0.06	1.48	5	20
3613	4.788	4.738	0.1	-0.06	1.48	5	20
3614	4.788	4.738	0.1	-0.06	1.48	5	20
3615	4.788	4.738	0.1	-0.06	1.48	5	20

Table 10- Program data (columns 62 to 69)

More info is shared, this time regarding the machine, and not the process, like temperature of critical bearings, or if there is any temperature compensation.

FrontBearingTemp	RearBearingTemp	StatorTemp	TempCompAdjustment	SerialNumber
23.3	22.8	22.3	0	_12345_____
23.7	23	23.4	0	_12345_____
26	24.8	25.4	0	_12345_____
25.9	24.9	25.6	0	_12345_____
25.9	25.1	25.6	0	_12345_____
25.9	25.3	25.9	0	_12345_____
26.2	25.7	26.4	0	_12345_____
26.4	26	26.9	0	_12345_____
26.6	26.2	27.8	0	_12345_____

Table 11- Program data (columns 70 to 74)

On the following are identified the type of bolts, how further the U side travelled, and the remaining are values referring the dimension of the hole, generated by the probe, that measure once every 5 (or 10, or 15, whatever chose by the costumer) holes.

CutterType	MaxForwardPosition	ProbeNumber	ProbeOffset	ProbeCSKOffset	D1Zero	D1-90
LockBolt	-179.161					
LockBolt	-179.161					
LockBolt	-179.161					
LockBolt	-179.161					
LockBolt	-179.161					
LockBolt	-179.161					
LockBolt	-179.161					
LockBolt	-179.161					
LockBolt	-179.161	1	4.879	-0.045	4.76	4.762

Table 12- Program data (columns 75 to 80)

The final information's are very important. Here it is possible to see if the machine properly competed some critical operation, the cycle time and, if problems occur, the codes of each issue. This is what gives us very useful information to work on.

Clamped	HoleDrilled	HoleProbed	SealantApplied	FastenerInstalled	CycleTime	Messages
						MSG220 MSG174 MSG086 MSG087 MSG560 MSG211
1	1	0	0	0	6.172	MSG253
1	1	0	0	0	5.916	MSG174 MSG087 MSG500 MSG174
1	1	0	0	0	5.316	MSG516
1	1	0	0	0	6.012	
1	1	0	0	0	5.968	

Table 13- Program data (columns 81 to 87)