Energy Efficiency Optimization in an Automotive Plant

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Abstract: The current EU energy legislation and the growing social awareness for environmental issues lead to the need of optimising the way energy resources are used. As a consequence of this important trend, this study focused in developing and applying a methodology that increases energy efficiency in an industrial plant of the automotive sector.

Several energy efficiency proposals were studied, within different areas inside the plant, but the emphasis went to the production sector and the compressed air system. It was estimated that the production equipment consumed 930MWh/year during non-production period, due to not being turned off. A generalised plan of shutdown for programmed and non-programmed stops that take longer than 60min would result in an energy reduction of 680MWh/year. The compressed air system was running with excessive pressure and the system leaks accounted for 35% of the air produced. It was proposed that the system operated at 7bar, which would not have influence on the equipment. As leaks inside the production equipment account for 94% of its total volumetric flow rate, it was proposed closing the valves when there is no air demand and the installation of electro valves. The combination of these measures would result in an energy reduction of 550MWh/year.

The implementation of all the proposals would result in an energy reduction of 1800MWh/year, which represents a decrease of 28,9% and 167000€/year savings. The emission of 845CO_2tons$_e$ would be avoided and all the 2023 legal energy targets would be met.

Key words: energy efficiency, production equipment, shutdown, compressed air, pressure, leaks.

1. Introduction

1.1. Motivation

The growing environmental conscience in the last two decades, supported by the significant increase in the emission of harmful gases to the atmosphere, has led to the establishing of various treats and protocols. These agreements, like Kyoto, Copenhagen or Durban, eventually guided to the definition of the 202020 targets by the European Union (EU) (1).

Energy efficiency projects are crucial in countries characterized by fragile economies and that deeply rely on fossil fuels from abroad (2) (3). As presented in Figure 1, in 2014 Portugal was importing 75% of its primary energy.

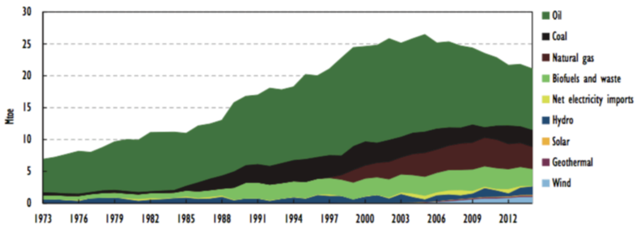

Figure 1: Primary energy consumption evolution (3)

Energy efficiency's constant actualization, together with the growing installed power of renewables, helps the economic vulnerable countries being less dependent from oil and gas price fluctuations (4).

The industrial sector represents 26% of the total final energy consumption in the EU (5). In Portugal, the sector has been losing relevance since 2000, reaching a consumption of 6Mtoe in 2014, but it is still the biggest energy consuming sector with 36% of final energy share (3). This fact could be explained by the comparatively low residential sector consumption, mainly due to its temperate climate when compared with other EU countries (6).

Oil, electricity, biofuels and natural gas are responsible for 34%, 23%, 19% e 18% of the industrial energy consumption, respectively (3). The values of fossil fuel consumed by the sector leaves the industry in a position of great energy dependency from the outside.

The 202020 policies were responsible for the targets set for the portuguese industry. The goals focus mainly on the increase of energy efficiency, which leads to the decrease of the ecologic footprint and the improvement of the sector's competitiveness.

1.2. Case of Study

The company chosen to develop and apply an energy efficiency methodology was Continental Teves in Palmela. The plant belongs to the german Continental group and started in 1998. The factory belongs to the division of *Chassis and Safety,* more precisely to the *Hidraulic Brake Systems* sector. Inside the plant were produced 4,4 mllions of car brake callipers in 2016.

1.3. Objectives

The main objective of this thesis is to analyse the energy consumption of Continental Palmela and establish energy efficient proposals that would decrease its energy intensity. The following objectives were outlined:

- Disaggregate the energy consumption of each area;
- Measure the potential energy savings;
- Suggest energy efficient proposals;
- Evaluate the financial viability of each proposal.

2. Legislation on energy consumption

In 2009, the EU established the 202020 energy policies and later on 2014, these objectives were extended calling it "Climate 2030" (7) (8). The energy targets are shown in Table 1.

Performance Indicators	2020 targets	2030 targets
Greenhouse gases reduction	20%	40%
Energy efficiency increase	20%	27%
Renewable primary energy	20%	27%

Table 1: EU energy targets

In Portugal, the intensive energy consumption management system (SGCIE) (9) was created to reduce energy consumption. This system forces the biggest energy consumers to implement energy efficient measures to reduce their energy intensity. The plan for rationalisation of energy consumption (PREn), that is outlined for every entity that consumes more than 500 toe of energy, has the following targets to be met until 2023 (10):

- 6% reduction of specific consumption (kWh/part) (based on 2015 values);
- 6% reduction of energy intensity (kWh/VAB);
- Carbon intensity value stabilization (CO2ton/kWh).

In the entire Continental group, environmental targets to be achieved until 2020 were defined, which are more ambitious than the defined by the PREn:

- 20% of energy consumption (2013 base values);
- 20% of CO_2 emissions reduction.

Continental also imposes the implementation of the ISO 50001 until the end of 2018 for every factory inside the group. This norm focuses on the implementation of procedures that lead to more efficient energy utilisation. It is based on the operationalization of an energy management system, on a continuous improvement philosophy. To achieve its continuous improvement method, it establishes a set of checkpoint (11):

- Development of an efficient energy policy;
- Set targets that to meet the energy policy;
- Decision making based on data;
- Result's analysis;
- Verify measure's effectiveness;
- Continuous development of the energy management system.

3. Industrial Plant Characterization

Continental's Palmela Plant, established in 1998, has 2 main buildings. In building 1 the steel parts are machined by a group of CNCs, while in building 2 all the calliper pieces are assembled together. Only the anchor and the housing, which are the two main parts of the calliper, are machined inside the plant. All the other components come from suppliers to be assembled.

3.1. Industrial Equipment

3.1.1. Building 1

Some of the 30 existing CNC machines work independently, while others operate integrated in semiautomatic production lines. From now on CNC machines will be designated as production equipment. There are 2 semiautomatic production lines for anchors (LS1 and LS2) and 4 for housings (LC1, LC2, LC3 and LC4).

The shopfloor lighting, refrigeration units and the industrial exhaust mechanism have a power of 26kW, 20kW and 60kW respectively. The last two were measured by ISQ during an energy audict.

3.1.2. Building 2

There are 7 assembly lines, which have robots, transport mechanisms and test units, where all the callipers parts are assembled together. The compressed air unit is located in this building. The system is composed by 3 air compressors, 2 air dryers, 3 air filters and a 10 m^3 buffer tank. There is 1 fix speed drive (FSD) 90kW compressor, the Ingersoll Rand MH160, which is a load/unload type of compressor, 1 90kW variable speed drive (VSD), Kaeser 90 and a 200kW VSD Atlas Copco. The Atlas was only installed in July, 2017, and since then has been the main compressor. Only the air compressed system was analysed in building 2, due to time and resources constraints. These systems are necessary to operate all the CNC machines, which makes them common to almost every industrial plant. It is often one of the biggest energy consuming systems in a plant and it is characterized by poor overall efficiency (12) (13).

3.2. Operations

The Palmela plant works 24/7 with three 8h shifts during the week and two 12h shifts on the weekend. The factory stops production an average of 10 days/year.

3.2.1. Production Equipment

The building 1 production record was used to characterize the production equipment utilization throughout the year. In this record are listed all the non-programmed stops that occurred in a period of time and there is information about when each stop happened, what kind of operation was performed and its duration. There was also information on the weekly duration of the programmed stops of each equipment. In Continental Palmela only the following actions are considered programmed stops:

- When there is no production due to production planning decision;
- Periodic maintenance.

All the other actions are considered non-programmed stops. With this data it was possible to know the exact amount of time that each equipment was in full operation and the amount of time in which it was stopped.

Figure 2 represents the percentage of time associated with each specific period, showing that only 58% of the total available time is productive. These values are the average between all equipment in building 1.

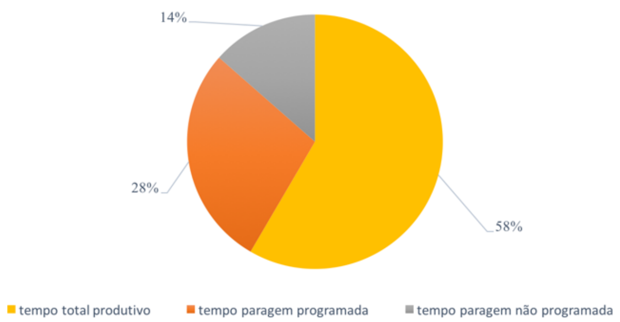

Figure 2: Production vs Non-production time

The majority of the non-programmed stops are short time stops, and there are between 5 to 50 of these actions each day, per equipment.

shows the distribution of the total non-programmed stops by type and duration.

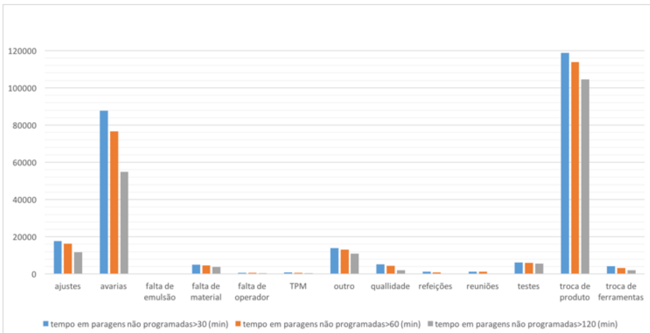

Figure 3: Total stoppage time by kind and duration

Change of products and breakouts are the main responsible for the non-programmed stoppage time, together achieving 80% of the total time in stops longer than 30 min.

3.2.2. Compressed Air

The compressed air system operates 365 days/year, even when there is no production. Before the integration of the Atlas Copco compressor in the system, there was only one possible setup, which was the MH160 working together with the Kaeser90. Not having any alternative could not only mean that the all factory had to stop in case of failure, but also that no maintenance was possible to perform on the compressors. The upside down of the integration of the Atlas was the incompatibility between the the compressor and the existing air management system (AMS). That meant that from the time it started operating as the main compressor it was not possible to extract data from the software.

Since the Atlas is faster adjusting the pressure to the system's needs, the pressure was reduced from 8,3 bar to 8 bar when this compressor is working. The average pressure variation dropped from 0,5bar with the former setup, to just 0,1 bar with the Atlas.

3.3. Energy Consumption

Through EDP's remote control system it was verified that in building 1, between June 2016 and June 2017, 4 950 MWh of electricity were consumed. The compressed air system consumed 1 689 MWh, during the same period.

As a consequence of being and intensive energy consumer, Continental Palmela was forced to optimize its energy efficiency, in order to achieve the goals set by the energy auditors, as shown in Table 2.

KPIs	2015 Values	Target for 2023
Energy Intensity **kgoe/VAB**	0,0641	0,0603
Specific Consumption **kgoe/part**	0,3345	0,3144
Carbon Intensity **tonC02e/toe**	2,1911	2,1911

Table 2: Legal target values

The average electricity price in 2016 was 0,107 €/kWh, with the price of active energy achieving 0,089 €/kWh. The peak hours load fee was 0,264 €/(kW.day). The peak hour tariff period in the summer happens during the day, which greatly benefits PV systems.

To measure long periods of electricity consumption, it is crucial to have energy analysers with storage capacity. Measurements that cover 7 days, and therefore the 19 shifts, are especially useful.

4. Methodology

The present study included energy efficiency analysis on the non-production area, water heating system, production equipment, lighting, compressed air and photovoltaic system. Although only the production equipment and compressed air system are analysed in this document, the final results include the contributions of the full study.

On the non-production area was proposed the integration of an air conditioning centralised management system.

To the water heating system was proposed the installation of an air-water heat pump to replace the thermo electric heaters.

The installation of LED lighting and solar tubes were proposed for the production area.

It was studied and suggested the integration of a 200 kWp photovoltaic system.

It was considered that every equipment power load profile followed the factory power demand. It was then considered the annual average active energy price, which was 0,089 €/kWh.

4.1. Production Equipment

CNC machines were initially grouped according to its machining specifications. At least 1 CNC per group was measured to guarantee the veracity of the results. Ideally, for these kind of machines, measurements covering production and non-production periods should be done, to be possible to estimate the energy consumption on both periods. If there is no possibility of performing long measurements, it should be done during a production period, but also covering some stoppages. Shift changes or lunch breaks are usually an interesting period for these tests.

It should be kept in mind that identical CNCs, machining the same product, may have different energy consumptions. Tools wear, different motors or even slightly different setups are among the possible causes for that to happen.

In the present study 4 main CNC groups were considered, distributed as shown in Table 3. These groups were created mainly having in consideration the kind of operations of the CNCs and the number of stations available. Hoffman machines have a couple of rails that slide up and down, like a milling machine. BA's are more advanced uni-station CNCs.

	Hoffman	BA's	Poli-station	Uni-station
Number	4	4	8	14

Table 3: CNC by type

The energy consumption of some CNCs that belong to semiautomatic lines were measured together with the whole line. The 6 semiautomatic production lines are composed by:

- LS_1: 1 Hoffman + 1 Poli-station
- LS_2: 1 Hoffman + 1 Poli-station
- LC_1: 2 Poli-station
- LC_2: 4 BA's + 2 Uni-station + 1 Hoffman
- LC_3: 1 Poli-station + 2 Uni-station
- LC_4: 2 Poli-station

LS_1 and LS_2 have similar layouts and CNC machines that produce identical products. LC_1, LC_3 and LC_4 also have similarities, even though having different layouts and CNCs.

The data collected in the measurements of some lines was then extrapolated to the others. The same was made in the independent machinery. There was also data from energy analysis made in 2015, such as Figure 4. It was verified that the production lines that were measured back in 2015 did not suffer major modifications. Its layout remained unchanged, as well as the product it produces.

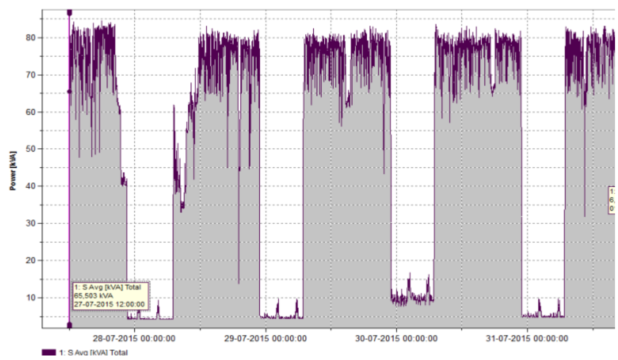

Figure 4: Load diagram from LS1

In this measurement, the production and non-production periods are clearly identified, since the first goes between 70kW and 80kW and the second between 5 kW and 10 kW.

To be possible to estimate CNC's energy consumption in larger periods of time, it was necessary to access the production record of all equipment. Using both data in parallel (energy measurements and production record) was possible to calculate the energy consumed in each period of production.

$$E_{prod} = P_{prod} * t_{prod} \quad (1)$$

$$NE_{prod} = NP_{prod} * Nt_{prod} \tag{2}$$

E_{prod}: Energy consumed in production period (kWh); NE_{prod}: Energy consumed in non-production period (kWh); P_{prod}: average load in production period (kW); NP_{prod}: average load in non-production period (kW); t_{prod}: production period (h); Nt_{prod}: non-production period (h).

Theoretically, every CNC should be in shutdown when it is not machining, but that is not always possible, due to the characteristics of the various non-programmed stops (14) (15).

The non-production time may be split in programmed and non-programmed stops, as presented previously. Within the non-programmed stops it was obvious that change of product and breakouts were the biggest contributors for down time. These results help to filter the most relevant from the least relevant data.

Relying on acquired data and on CNC's characteristics, the stoppage time should be established, from which the machines should go into shutdown, once it is not advisable to perform a full shutdown in stops under 10min. After discussing with the production and maintenance teams, a decision of shutting down the machines on stops expected to take more than 60min was made. This limit is a compromise between shutting down the equipment in every stop and consequently reach the biggest energy savings possible, with the real operational possibilities of executing a general shutdown procedure.

Given the importance of understanding the characteristics of each stop, its frequency and duration were studied.

The blue line in **Error! Reference source not found.** is the ratio between the number of stops bigger than 60min and the number of all stops. This represents the probability of a specific stop being longer than 60min. The orange line is the share of stoppage time associate with stops longer than 60min. Finally, the yellow line represents the percentage of energy consumption of each stop (only taking into account stops longer than 60min).

Analysing together the 3 lines suggests the energy savings potencial of each type of stop. For example, a high value among the 3 lines, like in change of product (troca de produto) at LC3 means that: the majority of stop takes longer than 60min (blue line); majority of the stopped time is due to stops longer than 60min (orange line); high percentage of energy consumption associated with this stop (yellow line); in conclusion, the equipment should be put in shutdown before any change of product. A distinct occasion

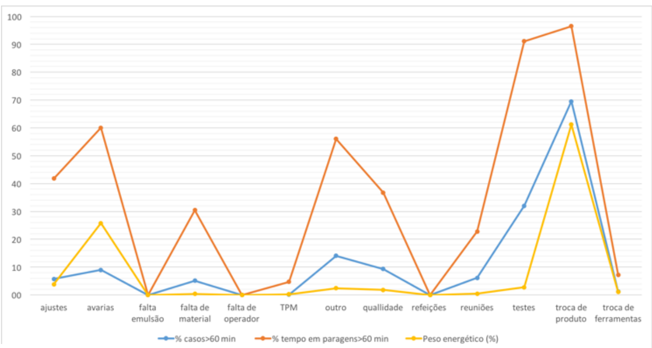

Figure 5: LC_3's stops

is, for instance, the lack of material stop (falta de material). Even though the orange line reaches almost 30%, since the yellow line is almost zero, it means this kind of stop is irrelevant in terms of energy consumption. The blue line also has a small value, meaning the probability of having a stop longer than 60min is also short. Consequently, it would be almost useless turning off the equipment before this type of stop.

Every equipment should have a non-programmed stop guide that indicates what action should be taken before each stop, as shown in Figure 6.

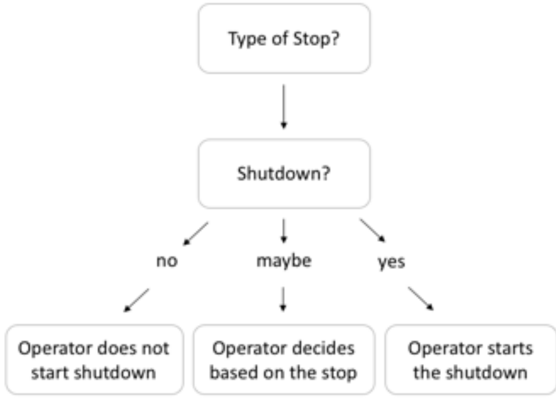

Figure 6: Shutdown work flow

Firstly, the operator should start by identifying the type of stop. Secondly, by following the designated flow, supported by his personal experience, should take a decision about shutting down, or not, the equipment before starting the stoppage procedure. A history for each machine and stop should be done as the stops occur, in order to collect the most possible data in order for it to help making better decisions. This is a critical phase because there are stops where it is really hard to estimate its probable duration.

In an initial phase of the system's implementation it was advised to do the shutdown only before change of products and breakouts. It was also advised to perform the shutdown only on the semiautomatic production lines and not on the independent CNCs.

Programmed stops, which are not covered in this analysis, are characterized by long maintenances which is ideal for a shutdown procedure. Even though it was not possible to access the records of these stops, due to its favourable characteristics, it was assumed that a full shutdown could be performed during that period.

After estimating the energy consumption with these calculations and extrapolations, it was necessary to compare the results obtained with the ones provided by EDP, like Figure 7. These values of electricity consumption provided by EDP are the total energy consumption in building 1 and because of that have to be carefully looked at.

This example is from a week in which the factory was partially operating during shift 1 and 2, but with no production or maintenance occurring during the third shift. Even though there was no need for any system to be turned on, there was an average electric power of around 200 kW being used during shift 3. This data backs up the referred need to standardize a general shutdown procedure.

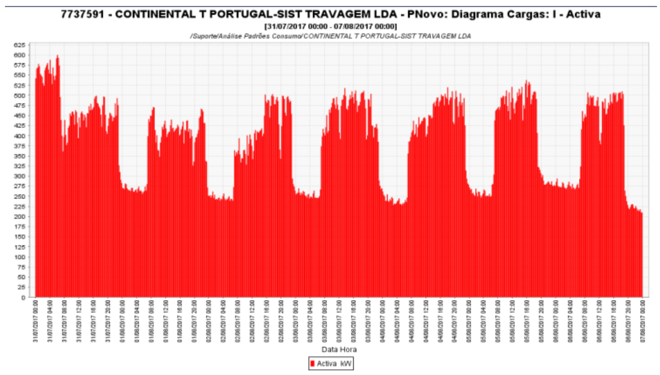

Figure 7: Load Diagram from building 1

4.2. Compressed Air

The integration of the Atlas VSD 200 meant that the air AMS system would not work while it was operating, which lead to the need of doing energy measurements to the compressor. The first measurement was performed during a regular, full production week, while the second was performed during a partial production week. Pressure and power profiles were obtained. The compressed air volumetric flow rate (VFR), was not possible to obtain, since there was no flow meter outside the compressor.

Analysing both pressure and power together enables to take the first conclusions over the system's behaviour. If the system is over or under dimensioned, it would be detected in one or both profile graphs. Figure 8 shows a period where the Atlas compressor was poorly working due to being over dimensioned for the air demand at that time. In this particular case, it was possible to identify the phenomenon looking only at the load graph, as the VSD compressor had to go into shutdown numerous times not to overcome the maximum system pressure.

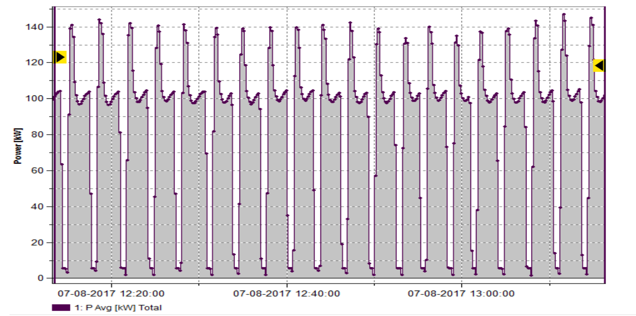

Figure 8: Load diagram of Atlas compressor

This specific event could have been solved if the Atlas was connected to the AMS, giving the possibility to alternate between machines. In Palmela, it was estimated that each year there are 240h of low compressed air demand and it is advisable to turn on the Kaese90 and turn off the Atlas during those periods.

Another analysis performed was related with air leaks. To perform this test was necessary to measure the power and VFR in a moment of zero air demand need. When the AMS was fully operating, all the data needed could be taken from the software. On the 16th of April 2017, when there was no production at the factory, it was possible to get the information needed to characterize the leaks in air system:

- Leak's air flow of 10 m^3/min;
- 64 kW of average power;
- 35% of the system's energy consumption;
- 560 000 kWh consumed;
- 7% of the plant's energy consumption.

Due to the high leak values in the system, a test was performed on the 22nd of September, 2017, a day without any air consumption, having two main goals:

- Verify if the air volume flow of leaks remained constant;
- Separate the leak's air volume flow of the supply piping from the equipment.

The old setup was turned on to supply data to the AMS and the power and air volume flow was registered. It was confirmed that the system was performing in the same way, having similar leaks air flow. In Palmela's plant, every equipment has a compressed air intake valve. Therefore, it was possible to close all the valves in the factory and consequently obtain the piping air flow leaks. Indirectly, the equipment air flow leaks were also calculated:

$$\dot{v}_{equip\ leaks} = \dot{v}_{total\ leaks} - \dot{v}_{piping\ leaks} \qquad 3$$

$\dot{v}_{equip\ leaks}$: leaks flow rate after equipment admission valve (m^3/min); $\dot{v}_{total\ leaks}$: leaks flow of the entire system (m^3/min); $\dot{v}_{piping\ leaks}$: leaks flow rate before equipment admission valve (m^3/min);

Following the same process, the air leaks associated power needed from the compressors was also calculated:

$$P_{\ equip\ leaks} = P_{total\ leaks} - P_{piping\ leaks} \qquad 4$$

$P_{equip\ leaks}$: compressor power to handle equipment's leaks (kW); $P_{total\ leaks}$: compressor power to handle all system's leaks (kW); $P_{piping\ leaks}$: compressor power to handle piping's leaks (kW);

Since it was possible to separate the equipment's air flow leaks from the ones in the supply piping, it was possible to quantify the energy saved if the valves were closed when there is no air demand.

$$E_{closed\ valves} = P_{equip\ leaks} * t_{shutdown} \qquad 5$$

$E_{closed\ valves}$: Energy saved when the valves are closed (kWh); $P_{equip\ leaks}$: power used by the compressors to supply the leaks air demand (kW); $t_{shutdown}$: shutdown period (h);

Periodic maintenance on all the pneumatic valves, cylinders and junctions, like is performed on the hydraulic system, are extremely important. Compressed air specialists say that a well designed and maintained system, should not have more than 15% of air leaks, which is much less than the 35% estimated in the present case (13) (16). The first goal is to reduce the leak's flow rate to just 25% of the total air flow rate, with a general maintenance performed during the equipment's periodic maintenance program. This first action should be as detailed as possible. When this first goal is achieved, the long term 15% goal should be targeted. To achieve it, pneumatic maintenance should be part of the periodic maintenance guidelines.

It was recommended the purchase of electro valves for every equipment, for it to automatically close the air supply whenever the equipment goes into shutdown. For the whole factory, the investment cost should not be greater than 10 000€.

The compressed air system running pressure is an extremely important subject in terms of energy savings. The majority of industrial pneumatic equipment has a minimum working pressure of 6bar (12). Due to the fact that any slight increase in pressure represents large amounts of energy (13) (5), it should be kept as close as possible to the 6bar mark, taking into consideration that there are always some pressure losses across the piping. The system pressure should be reduced slowly, not to endanger the production process, until reaching the minimum possible running pressure. Reducing 0,1bar/month could work as a rule of thumb, to allow enough time to correct any pneumatic problem that may occur due to pressure drop. There should be taken special attention to equipment in the end of the air piping, since it is the place with higher pressure drop. In the present case, it was verified that in the last section of the air supply pipe the pressure drop was 0,7bar.

To estimate the power required from the compressors for different running pressures, it was necessary to calculate the compressor overall efficiency. The overall efficiency was defined as the ratio between the isentropic compression power and the real compressor power. Equation 6 is used in the Brayton cycle for constant specific heat coefficients (5):

$$T_{out} = T_{in} * \left(\frac{p_{out}}{p_{in}}\right)^{\frac{k-1}{k}} \qquad 6$$

T_{out}: gas temperature at the end of compression in isentropic conditions (K); T_{in}: gas temperature before compression (K); p_{out}: gas pressure after compression (bar); p_{in}: gas pressure before compression; k: $k = cp/cv$, heat capacity ratio, for air: $k = 1{,}4$.

From thermodynamic tables (5), the enthalpy for each stage was obtained from the temperatures. Together with the mass flow rate obtained from the AMS it was possible to calculate the theoretical compressor power, through equation 7:

$$P_{\ comp\ ideal} = \dot{m} * (h_{out} - h_{in}) \qquad 7$$

$P_{comp\ ideal}$: theoretical compressor power (kW); $\dot{m}$: gas mass flow rate (kg/s); h_{out}: gas enthalpy at compressor exit, at T_{out} (kJ/kg); h_{in}: gas enthalpy at compressor inlet, at T_{in} (kJ/kg).

With the real compressor power obtained through the measurements done, it was possible to estimate the overall efficiency through equation 8:

$$Overall\ Eficciency = \frac{P_{Comp\ ideal}}{P_{Comp\ real}} \qquad 8$$

$Overall\ Eficciency$: ratio between the ideal and the real compressor power; $P_{Comp\ real}$: real compressor power (kW);

The overall compressor efficiency was used to do the inverse path to estimate real compressor power for different running pressures. The mass flow rate coefficient has to be correct since it varies with the change in pressure. The volumetric flow rate is constant because it only depends on the pneumatic equipment's intake volume, which means the change in air density is fully responsible for its variation. At the equipment's pneumatics, air temperature is considered to be ambient temperature.

$$\dot{m}_{p2} = \dot{m}_{p1} * \frac{\rho_2}{\rho_1} \qquad 9$$

$\dot{m}_{p2}$: mass flow rate at pressure p_2 (kg/s); $\dot{m}_{p1}$: mass flow rate at pressure p_1 (kg/s); $\rho2$: air density at pressure p_2 and ambient temperature (kg/m^3); $\rho1$: air density at pressure p_1 and ambient temperature (kg/m^3).

The air density can be calculated assuming it behaves as an ideal gas, through the equation 10:

$$\rho = \frac{p * M}{R * T} \qquad 10$$

ρ: air density(kg/m^3); p:air pressure(bar); R: perfect gas constant$\left(\frac{J}{K.mol}\right)$; M: air molar mass (kg/mol); T: air temperature (K).

Since there is almost no variation in the air temperature with the pressure change after this is cooled down by the compressor's radiator, the density ratio can be calculated as shown in equation 11:

$$\frac{\rho_2}{\rho_1} = \frac{p_2}{p_1} \qquad 11$$

The overall efficiency is the product of isentropic efficiency, mechanical efficiency and volumetric efficiency. This means it was required to know how each one of them varies to estimate the real compressor power in a more precise way. Since the mechanical and volumetric efficiencies, together, rely on the compressor rotation speed and on pressure ratio, it is highly probable its values change for different running pressures. As a consequence, and since this method assumes constant overall efficiency for all pressure ratios, it is vulnerable to errors which are hard to quantify. However, as it is more likely that the values of the two efficiencies together could go up when the pressure ratio decreases, it can be considered a conservative approach (18). The temperature in the compressors room is also an important factor because it influences its efficiency. For that reason, energy measurements should be done in different periods of the year to guarantee better results.

5. Results

The energy consumed by building 1, provided by EDP, was compared with the ones estimated from the application of the developed methodology. The values presented on Table 4 correspond to the period from the 1st of January of 2017 to the 31st of July of 2017. The compressor energy consumption was not included because it is connected to the electricity transformer on building 2.

Energia consumida no Edifício 1 [MWh]	
EDP edifício 1	3 056
Medições e metodologia	3 335

Table 4: Comparison between EDP values and the estimated

The energy value obtained with the measurements and extrapolations done have a deviation of 9% from the values presented by EDP. Knowing that lighting, exhaust system and refrigeration of building 1 represent 17%, it would be expected that production equipment should consume around 80% of the building's total energy. However, it was estimated that production equipment consumed 2796MWh on the same period of time. This value represents 91% of the building's energy consumption, which is 11 percentage points higher than expected. As the lighting, exhaust and refrigeration operate in known regimes during defined periods of time, it should not be the main factor of discrepancy. On the other hand, the many extrapolations and assumptions made for production equipment mean that it may be the biggest source of error. One of the main source of error could be the associated with the assumption made that machines were never on full shutdown, while on stoppage. Other possible error cause could be the extrapolations between similar production equipment. Assuming that production equipment behave always the same through time is also a highly probable source of errors, since components wear varies with time.

5.1. Production equipment

The energy consumption during production and non-production period was calculated by combining the energy measurements with the production record. The results showed that 19% of the production equipment's energy consumption happened during non-production time. It was estimated that production equipment consumed 400MWh monthly, from which 77MWh correspond to non-production periods. 44MWh is related with programmed stops, while 33MWh corresponds to non-programmed stops.

Figure 9 shows that the majority of the energy is consumed by the production lines, reaching near 80% of the total production equipment's energy consumption. Therefore, the shutdown procedure should always give special attention to these equipment.

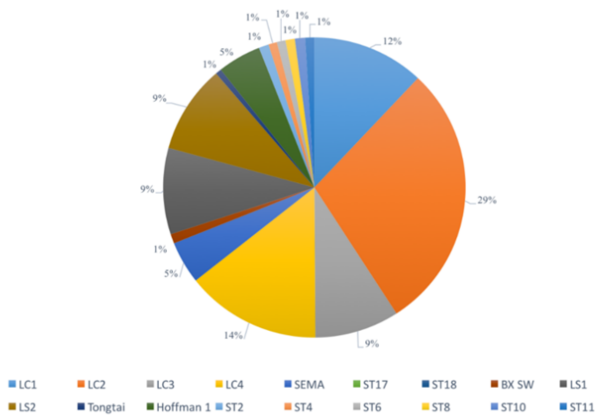

Figure 9: Energy consumption by equipment

Programmed stops together with non-programmed stops longer than 60min account for 86% of the total stopped time, which represents a big potential of energy reduction with these reforms. Figure 10 shows the share of each non-production period.

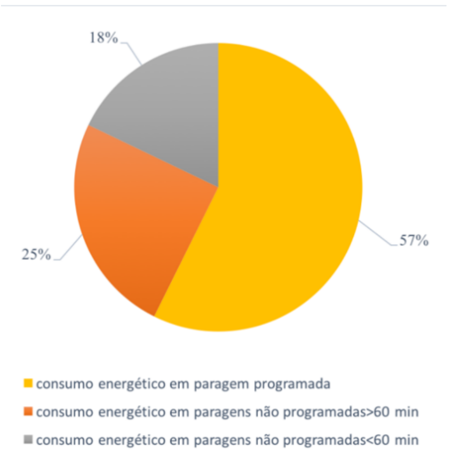

Figure 10: Non-production period's energy consumption

Considering that the maximum energy reduction's potential is the sum of the consumed energy during programmed stops and non-programmed stops longer than 60min, it would result in:

- Reduction of the energy consumption by a maximum of 760MWh/year.

If the shutdown was performed only before change of products and breakouts as well as during programmed stops, it is obtained:

- Reduction of the energy consumption in 680MWh/year;
- Savings of 60 500€/year.

These values do not include single machinery stops, and with the integration of those in a next phase of implementation, would be possible to increase the savings to 700MWh/year.

There was no payback calculation once it was considered that no financial investment is needed to implement this procedure. With a better coordination between the production engineering team with the maintenance team should be possible to standardize the shutdown procedure with no need for extra costs.

5.2. Compressed Air

All savings calculations include the compressed air consumption of the 2 buildings.

Firstly, the energy consumption of the Atlas during a production period was measured, where it was obtained a 181kW of average power. The second measurement, shown in Figure 11, took place during a week of partial production, where there was no production at all during the 3rd shift. The average week power was 89kW, but if only the 3rd shift is considered it drops to 72kW.

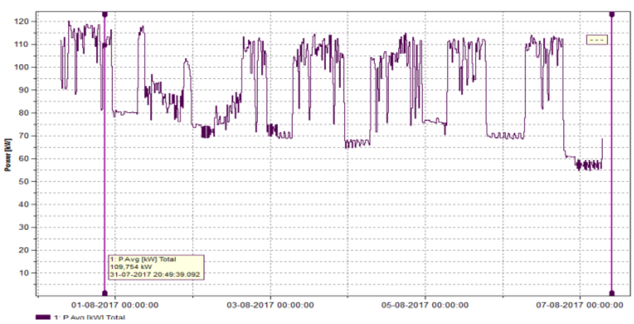

Figure 11: Atlas during a partial production week

Since the compressor was shutting down during the low air demand periods due to being oversized for that air flow, it was advised that it should be connected to the AMS in order to be automatically swapped for the Kaeser90 during these kind of periods. Analysing the technical data of the Atlas, it was observed that for a running pressure of 8bar, the air flow rate should not be lower than 13m^3/min to avoid the load/unload behaviour. For 8bar, the compressor only operates near its peak efficiency at volume flow rates higher than 23m^3/min, hence it should not run for longer periods under that value. Since in similar conditions it was verified through the AMS that the Kaeser90 needed only 50kW to maintain the defined system's pressure, the results with the compressor action during the 240h/year of low air demand, were:

- Power reduction of 22 kW during that period;
- Energy consumption decrease by 5 280 kWh/year;
- No investment needed;
- Savings of 470 €/year.

5.2.1. Compressed air leaks

Figure 12 shows the air flow rate during the air leaks test, when the air intake valves were closed. Under normal air demand circumstances, the compressor would run continuously and its VFR graph would show no operational breaks, which was the opposite from what is shown.

During the test the air leaks flow rate and the power those leaks demanded from the compressors were respectively:

- 0,7m^3/min;
- 6,8 kW.

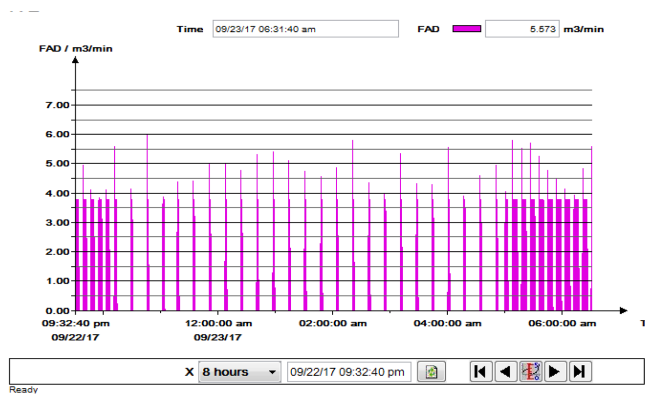

Figure 12: VFR of Kaeser 90 with valves closed and no air demand

It was concluded that 94% of the total air leaks flow rate happens from the equipment's valve downwards. As a consequence of the results, the closing valves procedure should be immediately implemented whenever there is no need of air supply in every equipment. This is a quite straightforward action plan, as the majority of equipment have only 1 air admission valve, taking no longer than 10s to close it.

Assuming, in a conservative approach, that it was only possible to close the equipment's valves during the programmed stops, which account for 2400h/year, it would result in:

- Power reduction of 57 kW (64kW-7kW);
- Energy reduction of 140 000 kWh/year;
- Savings of 12 460 €/year.

It was also assumed that the production equipment in building 2 had the same programmed stoppage average period.

The savings obtained with this action would allow the installation of electro valves in all equipment without the need of great financial sacrifices. Even though the whole process could be fully executed manually, there is also some uncertainty related to the enforcement of the procedure from the operators. Therefore, the target should be to achieve the full automation of these kind of procedure. The implementation of the electro valves, having a cost of less than 10000€, would also make the procedure almost imperceptible to the normal production process.

When the first target of 25% of air leaks is achieved, due to a rigid maintenance plan, it would lead to:

- Compressor power reduction of 18,5 kW;
- Energy reduction of 117 00 kWh/year;
- Savings of 10 400 €/year.

It was considered that production equipment need air in 72% of the available time, to be coherent with the previous assumption.

After achieving 25%, and if a target of just 15% of leaks is achieved, the results obtained would be:

- Compressor power reduction of 37 kW (from base level);
- Energy reduction of 232 00 kWh/year;
- Savings of 20 650 €/year.

5.2.2. Compressed air system pressure

Knowing all the pneumatic components should be ready to operate at 6bar and since there is a 0,7bar of pressure loss in the last section of the supply piping, the compressors should be set for a running pressure of 7 bar. Figure 13 shows the evolution of compressor power needed when the pressure drops.

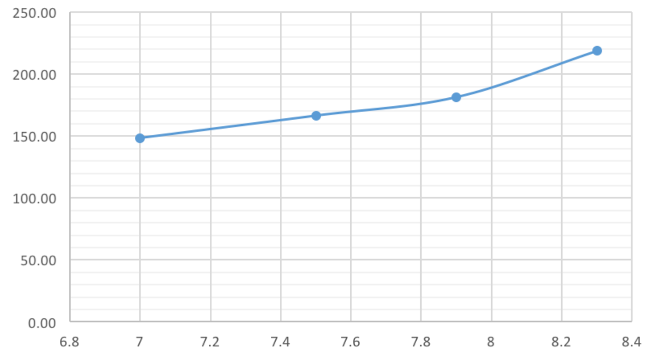

Figure 13: Power vs pressure for average flow rate

The reduction in pressure would result in:

- Energy reduction of 288 000 kWh/year (without leak energy reduction's contribution);
- No investment needed;
- Savings of 25 630€/year.

5.3. Key performance indicators (KPI)

Continental Palmela is an intensive energy consumer and consequentially has to meet the energy targets defined by the auditors. Table 5 shows the base and target values as well as the KPIs achieved with the introduction of all the proposals.

KPIs	Values from 2015	Target values for 2023	Results
Energy Intensity [kgep/VAB]	0,0641	0,0603	0,0508
Specific Consumption [kgep/unidade]	0,3345	0,3144	0,2649
Carbon Intensity [tonCO_2e/tep]	2,1911	2,1911	2,0822

Table 5: KPIs results after implementing the proposals

Energy intensity and specific consumption indicators show a total factory's energy reduction of 20,8% from the 2015's values. The carbon intensity KPI decreased due to the integration of a 200kW photovoltaic system.

Even though this extended abstract only included the analysis of the production equipment and compressed air system, all the areas presented on Table 6 were studied.

Proposal	Cost reduction [€/year]	Investment [€]	Payback [years]	Energy reduction [%]
Production area	72 248	66 000	0,9	13,1
Compressed air	48 960	10 000	0,2	8,8
Photovoltaic system	41 950	170 000	4,1	6,3
Water heating	3 177	5 000	1,4	0,6
Non-production area	665	10 000	13,3	0,1
Total	**167 000**	**261 000**	**1,5**	**28,9**

Table 6: Summary of all the proposals by area

6. Conclusion

The main goal of this study was the optimization of the energy efficiency of an industrial plant in order to meet the targets legally imposed.

On the production equipment it was verified that 42% of the time was non-production time and during that period the equipment consume 19% of its total energy consumption. This large value is the direct consequence of the equipment not being put in shutdown when not operating. Since the majority of the non-programmed stops are short occurrences, it was defined that shutdown procedure should start only before stops that take longer than 60min. A critical phase of the procedure is to estimate the duration of the stops. To simplify the procedure, in an initial phase it was defined that the equipment should only go into shutdown before changes of product and breakouts. This implementation would reduce energy consumption by 680 MWh/year.

The compressed air system at Continental was characterized by its high level of air leaks and excessive running pressure. It was studied the reduction from 8bar to 7bar. It was verified that at 7bar there is no production setbacks. The leak's volumetric air flow rate was 35% of the total air produced, and it was experimentally concluded that 94% of these leaks were allocated inside the equipment. It was then recommended to close the air intake valves whenever possible, as well as the installation of electro valves in every equipment. It was also established that it is urgent to perform detailed maintenances on all pneumatic components on a periodic basis, just like it is done on other major systems. These recommendations would reduce energy consumption by 550 MWh/year.

The integration of a 200kW photovoltaic system that would produce 6% of the plant's energy needs was also studied. The payback for this proposal is close to 4 years.

It was possible to reach an energy consumption reduction of 28,9%, corresponding to 1800 MWh/year, due to the implementation of all the proposals shown. These proposals also lead to a reduction of 845 tons of CO_2 emissions and that the KPIs reached the legal targets for 2023. Compressed air and production equipment proposals were the biggest contributors to the results achieved.

Longer energy measurements should be performed on the production equipment in order to reduce the uncertainties from the many extrapolations. The programmed stops of each equipment should be studied with the same detail as was done with the non-programmed ones.

More information must be collected concerning each specific non-programmed stop duration for the operators to decide upon the shutdown with less uncertainty.

In the future, flow meters should be installed in every equipment air intake as well as each compressor exit.

At last, a similar study should be done to the production equipment in building 2.

7. References

1. **EUROPEU, PARLAMENTO.** *DIRECTIVA 2009/28/CE.* s.l. : Jornal Oficial da União Europeia, 2009.

2. **Pordata.** Produtividade do trabalho, por hora de trabalho (UE28=100). *Pordata Base de dados Portugal Contemporâneo.* [Online] 2016. [Cited: 15 03 2018.] https://www.pordata.pt/Europa/Produtividade+do+trabalho++por+hora+de+trabalho+(UE28+100)-1992.

3. **IEA, International Energy Agency.** *Energy Policies of IEA Countries Portugal.* Paris : IEA Publications, 2016.

4. **Dias, Francisco Craveiro.** Oil price shocks and their effects on economic activity and prices: an application for Portugal . *Boletim económico.* 2013.

5. **ODYSSEE-MURE.** *Energy Efficiency Trends and Policies In Industry.* s.l. : ADEME, 2015.

6. **Eurostat.** Energy consumption in households. *Eurostat statistics explained.* [Online] 03 2018. http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households.

7. **Comission, European.** European Comission Climate Action. *2020 climate & energy package.* [Online] [Cited: 03 05 2017.] https://ec.europa.eu/clima/policies/strategies/2020_en#tab-0-0.

8. —. 2030 climate & energy framework. [Online] 2014. [Cited: 02 04 2018.] https://ec.europa.eu/clima/policies/strategies/2030_en.

9. **Inovação, Ministério da Economia e da.** Decreto-Lei n.º 71/2008. Lisboa : Diário da República, 15 4 2008.

10. **ADENE.** SGCIE - ENQUADRAMENTO E OBJETIVOS. [Online] [Cited: 20 08 2017.] http://sgcie.publico.adene.pt/SGCIE/Paginas/Enquadramento.aspx.

11. **ISO.** *ISO 50001 Energy management systems.* Geneve : ISO, 2016.

12. **Guide, Air Compressor.** Air Compressor Guide. *Air Compressor Guide.* [Online] [Cited: 5 12 2017.] http://www.air-compressor-guide.com/articles/the-cost-of-compressed-air.

13. **Energy, U.S. Department of Energy Energy Efficiency and Renewable.** *Improving Compressed Air System Performance.* Washington, DC : Compressed Air Challenge® , 2003.

14. *Best practices for energy-efficient machines.* **Green, Cindy.** [ed.] Eric R. Eissler. s.l. : Control Engineering, 29 05 2015, Control Engineering.

15. *Machine-tool Energy Efficiency: Current Issues* . **Weber, Chris.** [ed.] Control Engineering. s.l. : Control Engineering, 04 02 2012, Control Engineering.

16. **AirLeader.** *Compressor Management.* wiernsheim : WF Steuerungtechnik Gmbh, 2016.

17. **Michael J. Moran, Howard N. Shapiro, Daisie D. Boettner, Margaret B. Bailey.** *FUNDAMENTALS OF ENGINEERING THERMODYNAMICS.* s.l. : John Wiley & Sons, Inc, 1988.

18. **Eric Granyrd, Ingvar Ekroth, Per Lundqvist, Ake Melinder, Bjorn Palm, Peter Rohlin.** *Refrigeration Engineering.* Estocolmo : Royal Institute of Technology, KTH, 2011.

19. **Guide, Air Compressor.** Air Compressor Guide. *Air Compressor Guide.* [Online] [Cited: 5 Dezembro 2017.] http://www.air-compressor-guide.com/articles/the-cost-of-compressed-air.

20. **institute, CAGI-compressed air and gas.** Atlas copco cagi datasheets. [Online] [Cited: 25 08 2017.] https://www.atlascopco.com/en-us/compressors/cagi-data-sheets.