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Research article

A framework to reduce energy consumption in a press shop floor based on industrializable IIoT ($I3oT$)

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ABSTRACT

This article presents a framework to reduce energy consumption in a floor shop press based on Industrializable Industrial Internet of Things ($I3oT$). The $I3oT$ proposes the development of IIoT tools using the information available in the system, without adding any additional sensors. Based on this philosophy, we proposed to develop the C360 criterion in our previous works, which allowed to extract all the information available in the stamping presses for the development of $I3oT$ applications. In this article, we propose the development of a framework to optimize the parameters accessible from the C360 criterion for energy saving in the stamping process. Regarding the three parameters that can be modified and that affect energy consumption, that is, counterbalance pressure, tonnage and press speed, we will work with the first two in this paper. At the end of the article, the results obtained from the presses installed at Ford factory in Almussafes (Valencia) are shown based on their adjustment.

1. Introduction

In recent decades there has been a clear increase in the use of renewable energy in all sectors. Despite this, there is a lack of good infrastructure to obtain 100% from the supply of clean energy and stop relying entirely on hydrocarbons. In 2021, 61.8% of electricity was produced using fossil fuels, 9.85% with nuclear energy and 28.35% with renewable energies, with the most developed countries leading the way in this transition [1]. The concern for sustainable development of the planet and the acceleration of climate change are the main reasons for this change in trend, where new clean technologies are increasingly being used in different areas, both industrial and residential.

Numerous studies have been carried out to add value to the development of new technologies to produce energy sustainably [2]. But some of these information technologies, such as Big Data or Artificial Intelligence (AI), have contributed significantly to the development of more sustainable and efficient models of energy consumption and production, as well as the connection of this digital information with the physical world through the IoT, through sensors and specific instrumentation. Therefore, the main challenges of energy in the industrialization of the fourth industrial revolution are, on the one hand, the achievement of 100% sustainable and renewable energies, and on the other hand, the achievement of processes with the lowest consumption and the

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highest possible profitability, minimizing the degradation of energy sources. Many of the proposals made in the literature for the second assumption are based on monitoring and modelling the behaviour of the electrical consumption of equipment in order to improve energy management in industrial processes [3,4].

In [5], through the use of IoT technology, a system is defined for managing and monitoring the energy efficiency of a machining workshop. There are many approaches to energy management in manufacturing plants, such as the benchmark proposed in [6] to manage and analyse the energy of multiple equipment in mechanical manufacturing. Another approach may be the case of production planning and energy management in energy intensive industries, see [7].

There are also studies carried out with the purpose of saving energy in manufacturing processes by developing a Digital Twin, [8]. We have the case proposed in [9] in which the behaviour of energy consumption is modelled with a hybrid process through the use of petri-nets. In [10] a digital twin manufacturing system has been developed to describe the physical systems in virtual space, perform simulation analysis, make decisions and control the physical systems for various energy-saving purposes. The new concept “Digital Twin Shop-floor” was defined in [11] as a new paradigm for smart manufacturing in a shop-floor, and therefore defining a framework for energy consumption management [12]. More recently a multiscale model method for digital twin shop-floors has been proposed, see [13].

A great advantage that can be obtained from digital technologies in reducing the energy consumed is through the use of Smart Grid, with the technology in which an industrial plant is equipped, costs can be minimized by knowing the demand in real time. Using technology such as Blockchain [14] to obtain a smart grid with a secure system, providing security and privacy to costumer data through the use of P2P contracts [15] managing the energy load in different areas, whether industrial or domestic, even both at the same time. This technology gives us the great advantage of reducing the gap between the energy generated and the energy demanded through the application of artificial intelligence (AI) technologies [16], being able to predict future demand and be able to manage the energy supply efficiently.

In the stamping process, algorithms can be developed that allow us to detect anomalies for predictive maintenance as proposed in [17]. Through the analysis of energy loss in the stamping process, in [18] they are able to detect the clearance in the slide guide, providing important information for the preventive maintenance of the press. The press manufacturing parameters and energy consumption are directly related. In the research carried out in [19], based on the link that each monitored variable of the press has with energy consumption, they were able to obtain an optimal configuration to ensure the lowest possible energy consumption in a hydraulic press. Studies of energy consumption can also be found in the literature, such as the one proposed in [20], in which the energy consumption of a press-shop has been evaluated via a discrete event simulation.

1.1. Factory conditions in the fourth industrial revolution. Welcome to “the jungle”

The governance of factories, such as the ones in the automotive sector, is extremely complex. They use thousands of robots, grippers, cylinders, conveyor belts, etc., each with its components, electric motors, gears, chains, and each applied to different processes, such as welding, stamping, painting, etc. In addition, all this machinery interacts with the operators involved in different phases of the process, such as the assembling of components, verifying the quality of the parts, and, in some cases, with the ability to modify machine parameters to guarantee the productivity and quality of the parts. The goal of automation is none other than to try to eliminate dependence on that human factor. However, machines are not able to adapt to plant situations, which calls into question whether a complete automation of a factory without the human presence would be the most efficient, see for example, J.M. Haight et al. [21,22]. Thus, that operators can modify certain parameters of the machines responds to a reality in the manufacturing processes and is none other than variability. This variability can come from different sources, such as:

- *Two identical machines actually behave differently:* Many times machine or component manufacturers may provide curves to choose certain machine parameters that have been calculated under homogeneous laboratory conditions and as an average of tests with different components. In real situations, two identical machines or components may not be subjected to the same working conditions and in critical processes it cannot be extrapolated.
- *Lack of in-depth knowledge of the process:* There are processes, such as the stamping process, where there is no in-depth knowledge of how all the parameters affect the process. This means that, although manufacturers provide curves and parameters to adjust them, these are only indicative and need human intervention, that is, the operators’ intuitive skills and learning based on experience and therefore they can finish fine-tuning those types of parameters and achieve the right quality.
- *Technologies from different generations co-existing in the same factory and machine:* When a company buys an asset, whether it is a machine, robot or press, it will try to make it profitable over the years. When the machine breaks down and the broken component is replaced, it is usually more updated, which means that the machine will not behave the same.

At the Ford Valencia factory, the daily production is around 2,000 units. Any delay or quality failure that generates rework or scrap can result in large losses, since it will directly increase the cost of manufacturing the product. This will cause a very high level of pressure on both managers and other plant personnel since poor management that generates losses can be a ground for dismissal. When something goes wrong and you have to look for the cause, it may be difficult to find it, and this is where human intervention with its intuitive skills and experience-based learning can unlock the problem. For these reasons, employees call the factory by the nickname of *the Jungle*.

Table 1
Press Data in Real-Time.

Process value	Sensor quantity	Units
Tonnage Force	4	Tm
Cushion Cylinder Pressure	8	bar
Cushion Cylinder Position	2	mm
Counterbalance Pressure	1	bar
Overload Pressure	2	bar
Main Motor Speed	1	rev/min
Main Motor Power	1	kW
Main Motor Intensity	1	A
Press Speed	1	hit/min
Slide Position	1	mm

1.2. Previous works

1.2.1. $I3oT$ (Industrializable Industrial Internet of Things)

With the emergence of Industry 4.0 and its technologies, IIoT, Big Data, Digital and Hybrid Twins, AIs, etc., it is expected that all readjustments and problems currently existing in factories will be minimized or eliminated. There is an important limitation that is significantly slowing down its massive proliferation in the IIoT application industry. The installation of sensors, their wiring and data extraction through the IT network to the OT network, and adding the increasing number of machines or components to be sensorized, means that the proposed solutions do not end up being implemented in the industry in a massive way, due to the high cost involved in their implementation. In our previous works a new concept was proposed: the $I3oT$ (Industrial Internet of Things). The idea of this new concept is to use the installations already available in the factories to develop IIoT applications from them. The machines installed in the industry operate automatically and have sensors that provide the information received by the PLC to control the lines. The factories have an IT/OT network from which the machines communicate and the factory is managed. The $I3oT$ applications could be easily extrapolated and scalable to the rest of the systems at a very low cost.

1.2.2. $I3oT$ applications. Mini-Terms and C360 criteria

One of the first $I3oT$ applications developed in our previous works were the so-called *Mini-Terms* [23]. These are based on programming a timer in the PLC or PC-Line and, through the sensors installed for the normal operation of the line we can measure the time it takes for the line elements to perform their task. This data is sent through the OT and IT networks for analysis and processing. A deterioration in time is an indicator that the component is near the end of its useful life and may produce a line stoppage and therefore, when detected, an alarm will be sent to maintenance operators. The great advantage of the *Mini-Terms* is that there is no need to install new sensors and their industrialization is immediate. Currently, at Ford factory in Almussafes (Valencia) there are more than 36,000 elements or components under surveillance with this technology, generating important benefits, such as the increase in Technical Availability (TAV $> 6\%$), see [23]. Following the *Mini-Terms* philosophy, in our previous works we analysed the accessible parameters of the [24] stamping process for the development of *I3oT* applications, as the one known as *Criterion-360*. With this new criterion we can obtain 360 values of each of the parameters measured in a stamping cycle. Each of the 360 values represents a rotation of 1° of the press flywheel, being a complete rotation, which is all the necessary movement (lowering, stamping and raising) for the manufacture of a part. The free variables accessible in the press and which are part of the *Criterion-360* are shown in Table 1.

One of the applications *I3oT* using this criterion was the monitoring of the virtual gravity centre of the press through the Tonnage sensors [25]. This real-time monitoring allows us to know the status of the stamping stroke, ensuring that it is as centred as possible, preventing the wear of both mechanical elements of the press and the die, and the appearance of unexpected faults, thus ensuring the correct health of the press.

2. Goal of the paper

The objective of this work is to develop a framework $I3oT$ for the stamping process based on the *Criterion-360*, which allows us to optimize the energy consumption of stamping presses, without reducing production capacity and part quality. The stamping process is one of the most complex processes and depends on a multitude of parameters, many of them unknown, such as friction [26]. There are a large number of researchers working on this type of processes, organizing international conferences, such as the *Conference of the International Deep Drawing Research Group, IDDRG*, which celebrated its 42nd edition in 2023.

Press manufacturers usually provide orientation curves for the selection of the parameters but this value is not usually the one found in the presses configuration, either because the curve does not fit the specific press or because the operators have directly modified it under their experience to guarantee the quality of the part. When a new part is manufactured, the company's staff usually performs the relevant simulations beforehand to ensure that it can be manufactured. However, when the slide is assembled and the first tests are carried out, the quality may not be as expected. At that time, a parameter correction process will be carried out and the die operators may have to increase lubrication in certain areas and even sand certain parts of the mould to smooth curves and avoid quality failures.

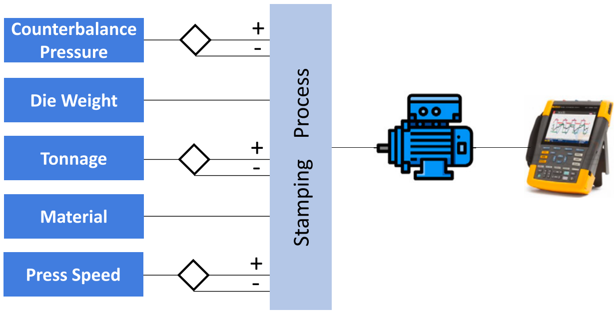

Fig. 1. Diagram of the variables that affect energy.

This article will analyse how the energy changes according to the multiple parameters that can affect the consumption of the real press of the industry and will analyse the feasible parameters to be modified in order to achieve a functional *I3oT* application that allows them to be adjusted in real time, without affecting the part quality and the daily production rate.

The paper is divided in 7 sections. In section 3, the framework to reduce de energy consumption is explained. In section 4 we will the energy behaviour of each press depending of their configuration and how we obtain the energy data. In section 5 we will explain the methodology used to optimise the energy without affecting production. In section 6 we will show the results obtained. Finally, in section 7 we will show the conclusions.

3. Framework to reduce energy consumption in an industrial stamping process

The stamping process is one of the most complex in the automotive industry due to the geometries to be achieved through plastic deformation and the number of parameters to be adjusted. In addition to the necessary equipment, the dies are very heavy elements, up to 50 tons, and the stamping lines are also formed by large presses to be able to handle those dies and manufacture the large number of parts required in a factory. This process allows a large number of pieces to be manufactured in short periods of time at a very economical price, which makes it a flexible and dynamic process. More than 40 variables are involved, taking into account the material to be used, the die and the press itself. Of all the parameters involved in the stamping process, there are 5 variables that have a direct relationship with the variation in the energy consumption of the press as we can see in the Fig. 1 and these are,

- Counterbalance pressure
- Die weight
- Press force (Tonnage)
- Material
- Press speed

Three of them can be modified to adjust energy consumption during the manufacturing process modifying the parameters of the variables in the machine control, which we know their value in real time because we have accessibility to them using Criterion-360, see Table 1. These parameters are the speed of the press, the pressure exerted in the stamping (tonnage) and the counterbalance pressure since the weight of the matrix and the material will not vary during manufacturing. The first two can affect the quality of the product if their adjustment is not adequate, the third variable only intervenes in the process as an auxiliary element of the press, making it have an equitable consumption throughout the cycle. The counterbalance pressure opposes resistance in the downward movement of the press, to subsequently facilitate the uplifting of the slide with the die and avoid reaching a high peak power when the press needs more force.

Adjusting the parameters requires a high degree of experience, otherwise quality defects may occur, production requirements may not be met, and even major breakdowns may occur in the press. Therefore, you have to be careful and carry out a more exhaustive control of the process when working parameters are modified, in *the Jungle* the most general way of working is through trial and error because of the reduced time margins to solve problems in an industry as demanding as the automotive.

The variables evaluated in the proposed paper will be those that we can modify in the control process and affect energy consumption. The Table 2 shows the variables that we are going to work on to reduce energy consumption with respect to how they affect manufacturing requirements.

In the automotive industry there are other factors to take into account apart from energy consumption, these are the quality of the manufactured product, fulfilling production demands and achieving a good maintenance of the equipment to avoid unexpected breakdowns. As a general rule, these requirements will go ahead of energy consumption, we seek to optimize the process and reduce resource consumption as much as possible, but if this affects other factors to be met in the delivery of the final product, we will not be able to proceed with its adjustment.

The table shows that a tonnage adjustment can directly affect the quality of the product and the press condition, where applying an incorrect effort will lead to poor shaping of the final product and excessive wear of the press leading to breakdowns. The counterbalance pressure is an auxiliary element of the press whose purpose is to support the movement of the press during the cycle,

Table 2
Correlation of work parameters with process requirements.

	Production	Quality	Equipment
Tonnage	✗	✓	✓
Counterbalance	✗	✗	✓
Press speed	✓	✓	✗

making it easier to carry out the upward movement of the die after forming the part, its adjustment it does not affect product quality or production delivery times. On the other hand, the speed of the press is directly related to the production and quality of the final product.

3.1. Press force (tonnage)

The value of the tonnage made by the press during the stamping cycle depends directly on the part to be manufactured. This part may have greater or lesser thickness, tensile strength or type of geometry, therefore it is not the same manufacturing a part with a 50 mm drawing and large radii as making a folded sheet. The tonnage required will vary from the pre-established design requirements for each part.

But when we focus on a piece, we can control this tonnage with press parameters such as the slide adjustment and the pressure exerted on the drawbeds of the die. With the adjustment, we modify the initial position of the top die in order to make a greater or lesser stroke. We are talking about an adjustment of tenths of a millimetre, since modifying several millimetres in height can cause serious problems, both for the press and the die. Or, on the other hand, the piece may be deformed if we increase the height and therefore the stamping may not be carried out correctly.

Another parameter that can modify the force made by the press is the coefficient of friction. An excess of lubrication would slide the part too much inside the die and the same would happen with the opposite, lack of lubrication will require a greater effort of the press to overcome the frictional force between surfaces of the die and material.

3.2. Counterbalance pressure

The counterbalance pressure of the process is measured from large volume cylinders installed on the sides of the press, which connected to the mobile part where the die is campled, the slide, help the electric motor when lifting the tons of iron that make up the die. These cylinders have the chamber filled with air before starting the cycle at a defined pressure according to the weight of the upper die. When they go down, the air is compressed and the pressure may increase by an amount of approximately 2-3 bars depending on the press. Once the stamping has been carried out, the press raises the die and the cylinders help in the upward movement where the pressure of the chambers drops to its set point. This component of the press helps to ensure that there are no consumption peaks at the time of the upward movement by the electric motor.

3.3. Press speed and/or loading and unloading robots

The speed of the press and industrial robots is controlled through their corresponding parameters. In robots, it is usually a percentage of their maximum speed ($0 - 100\%$). The speed adjustment of the machines for energy savings has already been discussed in our previous work. The measurement of the mini-terms or failing that, the cycle time, allow to detect the bottleneck, which is a slower process, and readjust the speed of the rest, see [27].

Regarding the quality of a cart part, the speed of the press has a direct impact, since at a lower speed, the better forming of the part, a fluid deepdrawing is carried out and at a higher speed it is possible that craks or wrinkles appear due to obtaining a bad forming, so the aim is to work at press speeds that are efficient for the process and do not affect the quality product, so modifying this parameter does not give much room for manoeuvre.

To define the production program the speed of the press is taken as the reference parameter, obtaining the pieces per minute that the line is capable of manufacturing. With manufacturing batches that can easily reach more than 5000 pieces, an adjustment of the press speed seeking to reduce energy consumption can affect the delivery times of the parts in the following processes, this is understood directly as losses, which does not make possible the adjustment.

3.4. Tool and material

We can assure that the same press will have different behaviour in terms of energy consumption depending on the material used and the tool used. Furthermore, during manufacturing, the weight of the tool and the characteristics of the sheet introduced in the process cannot be modified, they are considered to be the same. This is why the focus of this study will be on the adjustment of the parameters for each of the manufactured car parts in a press, minimizing consumption using the methodology explained in the 5 section. This is why these two variables have been discarded despite modifying the energy behaviour of a press.

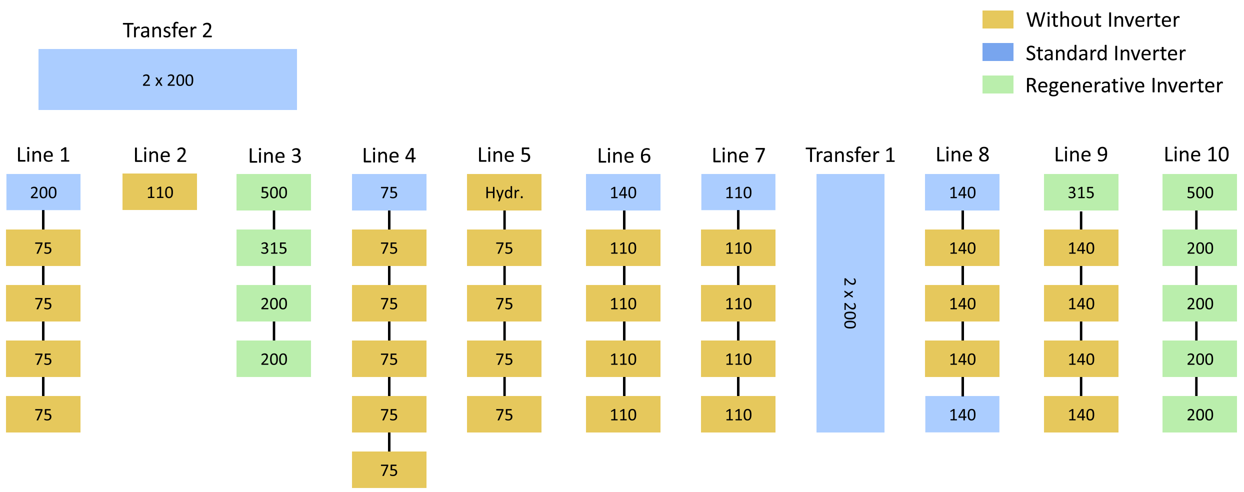

Fig. 2. Press shop layout diagram. Information of power of main electrical motor and type of power supply.

4. Energy consumption in the press shop

At Ford stamping plant in Valencia there are a total of 12 stamping lines and 4 cutting lines, with a total amount of 52 presses. They are mechanical type except the header of the line 5 which is hydraulic press. There are presses equipped with electric motors with power that may vary from $75kW$ in the smallest presses, to $500kW$ in the presses that carry out the drawing process of larger parts, as is indicated in the number inside the boxes shown in Fig. 2, every box in the figure represent an industrial stamping press. The colour of the box defines the type of inverter equipped in the press as it is shown in the legend of the figure.

The mechanical presses transmit the movement to a flywheel that stores energy and in turn this transmits it to the eccentric system that activates the movement of the press in each cycle. There are parts of different sizes depending on the force required for each operation, ranging from presses of 800 tons to presses of 2500 tons of force, so the electric motors for each one will have different power that may cause a higher or lower consumption depending on the operation carried out.

4.1. Electricity consumption in presses

Performing a basic energy analysis, we can observe that kinetic energy depends on mass and speed squared while potential energy depends mainly on mass and height. Systems that move at high speed, such as manipulator robots, or systems that move very heavy masses are the systems most likely to generate large energy savings if we optimize their operating parameters. The stamping process meets both requirements as it moves very heavy masses when moving the die and it has manipulator robots that extract and insert the parts into the press.

On average, a press performs approximately 1000000 cycles per year and the average energy consumed per stroke is around 90 Wh, that is, more than 4.6 GWh per year, only at the time the press is in motion. Taking into account the moment of transport, loading and unloading of the part to be manufactured in the press plus the auxiliary equipment in the process, the actual consumption of the plant is much higher.

When analysing the behaviour of electricity consumption along an entire stamping line, there are multiple possibilities for improvement for presses, robots and other auxiliary elements that make it up [20]. In [19] the energy behaviour of a hydraulic press under laboratory conditions is described and the parameters of the stamping process that directly affect consumption are also analysed, locating the optimal zone of configuration values of the stamping process.

One of the handicaps found when using IIoT applications is the variability of technologies used since when a company buys an asset, whether it is a machine, robot or press, it will try to make it profitable over the years. Focusing our attention on the type of electrical supply to the motors of the presses, as defined in Fig. 2, the oldest presses, up to 50 years old, are activated by direct power from the network, i.e., without inverters. Over time, inverters have been installed in the presses in order to improve the energy efficiency of the plant and therefore providing better performance. The most modern ones already have a regenerative inverter that, in addition to providing optimal consumption, returns energy to the network, being the most efficient presses used in the press shop. Therefore, for each type of electrical activation of the presses, depending on the inverter, the measured signals will have a different behaviour. These systems are described in the following subsections.

4.1.1. Regenerative inverter

The presses with regenerative inverters are the most efficient ones in the entire plant. They make it possible to return the energy accumulated in the flywheel to the power network. The measured signal of the power supplied to the motor is shown in Fig. 3 and we can easily see in which phase of the cycle we are at each moment. The area marked in yellow is the moment when the press is stopped, during the idle operation carried out by the line robots. The area marked in green is the time when the press performs the

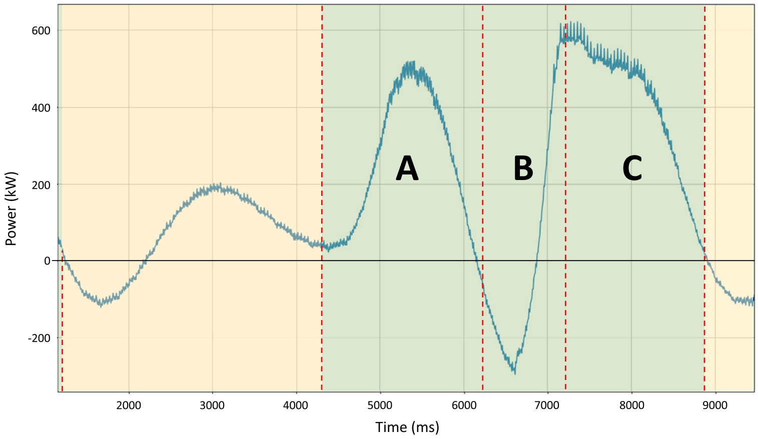

Fig. 3. Press with regenerative inverter. Power measured in one cycle (green area).

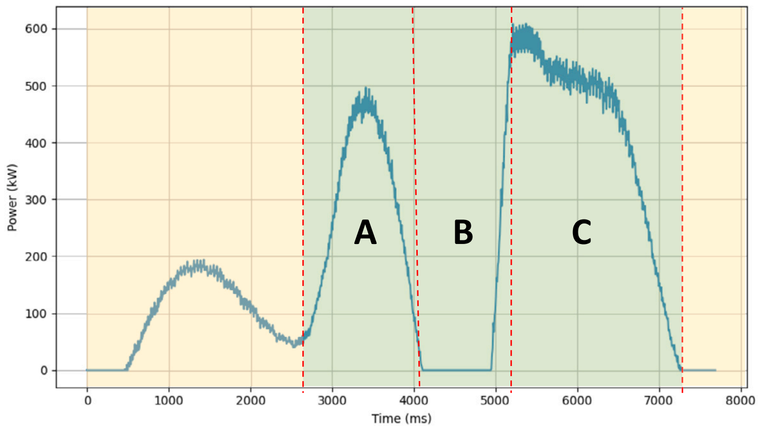

Fig. 4. Press with standard inverter. Power measured in one cycle (green area).

stamping cycle. The A area would be the downward motion, the B area is the stamping motion and the C area is the upward motion until the press stops.

In Fig. 3 we can easily see the difference between a regenerative and a non-regenerative inverter. When the value of the power supplied is negative, energy is being returned to the power network, taking advantage of the surplus supplied energy stored in the flywheel. This is when the electric motor acts as a dynamo and therefore due to the regenerative inverter this energy is not wasted.

4.1.2. Standard inverter

With this type of inverters we can significantly improve energy efficiency compared to presses that lack inverter. This is due to the accumulation of energy in the flywheel of the press, when the power delivered to the press is 0 kW as we can see in Fig. 4. The energy accumulated in the flywheel allows it to rotate without the need to manage torque on the electric motor. The measured signal of the power supplied to the motor with standard inverter is shown in Fig. 4.

Unlike regenerative inverters, in this case no power is returned to the network. This energy generated by the electric motor when it acts as a dynamo is sent to a resistor, so there is still some waste which means that we could reduce consumption even more. This is achieved in presses with a regenerative inverter as shown in the following section.

4.1.3. Presses without inverter

Most of the presses in the press shop do not have inverters at the moment. They are the least efficient ones in terms of energy consumption. The network power is delivered directly to the electric motor to activate the press operation.

As seen in Fig. 5 the power delivery is constant at all times. We always have the power supplied above 0, therefore there will be always a constant energy supply.

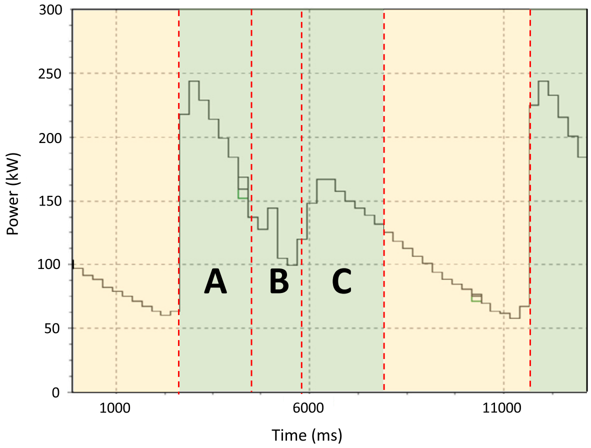

Fig. 5. Press without inverter. Power measured in one cycle (green area).

4.2. Measurement of power consumption

To obtain the energy consumed by the presses, it has been measured by two methods. The first method used in presses equipped with a CPU that allowed data to be obtained and extracted directly from the PLC that controls the press. Acquiring the data in real time thanks to the *Criterio-360* for these presses the CPU that manage the process is a PLC model Siemens CPU 317-2 DP, which with the connectivity that the presses present we are able to obtain the value of the power consumed. The second method used in older presses where they do not have good connectivity, the equipment *The 438-II Power Quality Analyzer & Motor Analyzer* has been used, as in the case of the signal shown for the press without inverter in the previous section.

As we have three types of press machines regarding the type of inverter, there are presses in which we can directly measure energy and others in which we can measure the power supplied at all times. The energy can be calculated from the expression

$$E_p = \int_0^t P_M(t)\,dt, \tag{1}$$

where the energy consumed by the press is E_p and the power consumed by the electric motor is $P_M(t)$. However, when trying to generalize the solution following the $I3oT$ philosophy and not taking into account the connectivity presented by the press, the data area will be obtained by approximating the function obtained from the data measured using Simpson's rule,

$$\int_a^b f(x)dx \approx \frac{b-a}{6}\left[f(a) + 4f\left(\frac{a+b}{2}\right) + f(b)\right]. \tag{2}$$

Thus, regardless of the way in which the process data is measured, no matter what, if we obtain the energy consumed by a motor or the power supplied. With which we will generically obtain our reference value applying Simpson's rule to the measured data, seeking to reduce the area under the function by modifying working parameters, if required, to reduce energy consumption.

5. Methodology to obtain optimal parameters

5.1. Determination of the optimal counterbalance pressure

In order to determine the optimal value of the counterbalance pressure, the set-point value in the machine will be varied by ± 1 bar, from 0.2 by 0.2 bars and therefore obtaining up to 10 values of energy consumed for each adjusted counterbalance pressure.

Once we have these data, a polynomial approximation is carried out, using for example a spline, which gives us a result as the one shown in Fig. 6. From that function, $p(x) \simeq f(x)$, the minimum of this function can be calculated by the gradient descent method.

$$x_{n+1} = x_n - \alpha \nabla f(x_n), \tag{3}$$

In the example shown in Fig. 6 we can see that the minimum energy point for this item is 4.5 bars of the counterbalance pressure.

The methodology to ensure minimum consumption of a press is divided into three phases. The first one is obtaining the data, sending and storing it. The second phase is the treatment of these data to know what is happening. And the third phase is the adjustment of the press based on the result obtained. On the one hand, we have the routine programmed in the press PLC where we will prepare the process information for further analysis in the processing layer. On the other hand, we will carry out the analysis of the data on our server with the algorithm that finds the minimum energy in order to finally send the PLC the value it has to adjust. Below we show the algorithms programmed in the different devices for a correct operation of the presented tool.

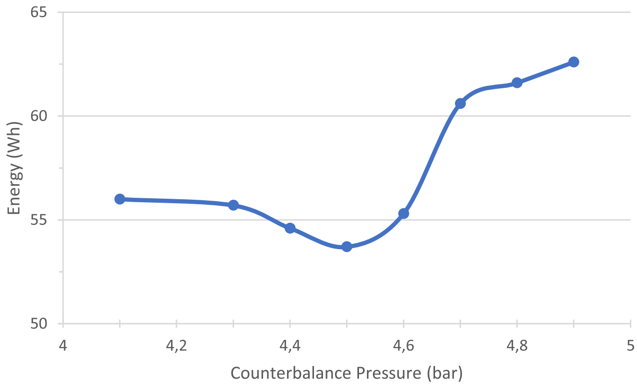

Fig. 6. Energy consumption per stamping cycle for a range of counterbalance pressure.

Algorithm 1: PLC routine to send required data.

```
Data: cpR: Real counterbalance pressure
Data: cpS: Set Counterbalance pressure
Data: w: Window of Count. Press. to analyze
Function getEnergyDataPerCP(cpR, cpS):
    cpRange ← array[ ] ;                                  /* Init pressure */
    energy ← array[ ] ;                                   /* Init enegy */
    if cpR ≠ cpS then
        sendAlarm();
        exit();
    end
    i ← cpR − w;
    while i < cpR + w do
        cpRange.append(i);
        energy.append(C360Energy(i));
        i ← i + (w/10);
    end
    return cpRange, energy
end
```

Algorithm 2: To obtain minimun energy consumption.

```
Data: c360energy: Arrays with energy data from PLC
Data: cpRan: Count. pressure data from PLC
Data: cpR: Real counterbalance pressure
eneRan ← array[ ] ;                                       /* Init. enegy range */
for energyArray in c360energy do
    ener ← simpsons(energyArray);
    eneRan.append(ener);
end
fx ← spline(cpRan, eneRan);
pCompOpt ← gradientMethod(fx);
if pCompOpt ≠ cpR then
    sendValuetoPlc(pCompOpt);
end
```

5.1.1. Routine in PLC

In this case, we will take as values of the actual process the counterbalance pressure and the set-point pressure, which must coincide ensuring that there is no problem in the hydraulic circuit. If we find a difference between them, it is because there is some reason why we cannot reach the pre-adjusted set-point pressure. We will define a window or range of the counterbalance pressure to be analysed defined as w. We will measure the energy for each of the pressure settings and then send the data to the server.

5.1.2. Server algorithm

The server algorithm works in such a way that we can get the different energy measurements for each configuration of the counterbalance pressure stored in the database, apply Simpson's rule, obtain the means of the energies, approximate using the spline method and seek the minimum with the gradient descent method. Once the optimal result is obtained, it is sent to the PLC to adjust it to the correct value if it is not the corresponding one.

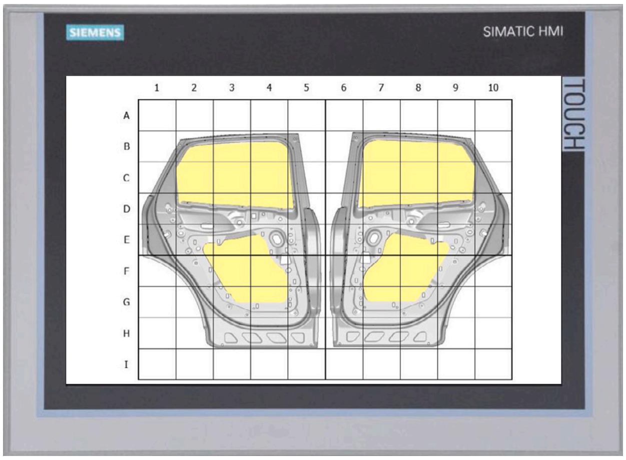

Fig. 7. End of line defect indicator.

5.1.3. Management strategy

During the manufacturing process of the parts the press speeds and tonnage values may be adjusted due to various factors. Although they all affect the value of the energy consumed by the press, they do not affect the optimum point of the counterbalance value, since this parameter is only affected by the die change. Therefore, this algorithm will run when a die is changed and only the first time it is used.

5.2. Determination of optimal slide adjustment (Tonnage)

The adjustment is defined according to the movement that the press has to perform with respect to the geometry of the die, the height of the upper and lower die and the drawing distance. In addition, if it is of simple action, the movement of the cushion cylinders where the blank holder rests must be added. During the try-out tests carried out by the plant staff, the regulation value can be adjusted for several reasons. Generally in parts with complex geometries in which there may be forming problems, the regulation is modified to make a greater tightening if wrinkles come out or it is reduced if there is excessive tightening as cracks may appear. Both quality defects cause the manufactured part to be classified as scrap and removed from the production batch.

Thanks to the developed tool presented in our previous work [25] where we are monitoring the tonnage for every press cycle, the methodology is as follows. When detecting previously known values outside normal working condition the system sends an alarm with detailed information about the event. So a try-out is scheduled to adjust slide adjustment parameter, while assuring quality of the manufactured product, to reduce the energy consumption.

To date, there is no automatic defect detection system that ensures 100% of quality defects within the cycle time required by the process. The review at the end of the line is carried out by visual inspection and the technicians through a screen as shown in Fig. 7 input the type of defect detected and then stored in the database. This allows us to identify in which cycle the defect has been detected and analyse the process data that has been monitored. Therefore, we cannot automatically have feedback on the output pieces to cross-reference it with the effort made by the press. So by monitoring the effort, the tonnage must be manually reduced to reduce consumption without affecting the product. That is why in the proposed methodology to reduce the energy consumed by the press in the present section, it is spitted in two parts, one with an automatically adjustment for the counterbalance pressure and one to manually adjust by try-out testing for tonnage.

6. Results

6.1. Counterbalance pressure

First, measurements have been made for several items within the pressure range in which we can modify the counterbalance pressure. The energy has been measured for several strokes and an average result has been obtained.

We can see that all three cases have a minimum consumption point depending on the weight of the die.

Chart a) shows a car part of line 1, press 1 where we have a deep drawing press with a 200 kW electric motor with larger dies and higher consumption compared to the other 2. Chart b) and c) correspond to press 3 of line 8, more specifically to items 2 and 9 respectively, which are shown in the results Table 3.

In this study we are going to focus on mechanical presses, which are the majority of those we have in the plant, and of the 3 possible configurations, we are going to show the case of a press without an inverter because it is the least efficient.

To obtain this percentage of energy saving, we have measured the consumption of the press for 20 strokes under the previously configured counterbalance pressure before modifying it to the optimal one. The average consumption is obtained to find out how

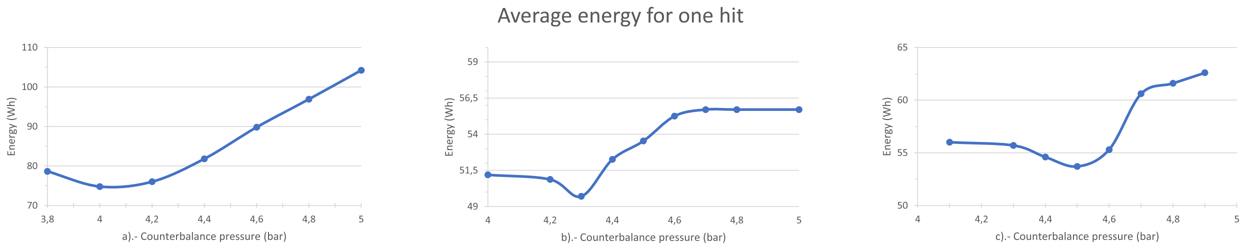

Fig. 8. Energy consumption per stamping cycle for a range of counterbalance pressure. Three different car parts.

Table 3
Press process data to optimize energy consumption.

	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10
Top Die Weight (T)	9.7	9.7	11.5	8.3	5.9	10	11.5	12.5	12.2	13
Bottom Die Weight (T)	9.6	9.6	10.7	13.9	7	10.3	13.6	12.3	14.1	14.2
Die Set Weight (T)	19.3	19.3	22.2	22.2	12.9	20.3	25.1	24.8	26.3	27.2
Actual Count. Pres.	4	4.2	4.1	4.5	4	4.5	4.3	4.5	4.9	4.5
Theoretical Count. Pres.	4.3	4.3	4.4	4.2	4	4.3	4.4	4.6	4.5	4.6
Δ Count. Pres.	0.3	0.1	0.3	0.3	0	0.2	0.1	0.1	0.4	0.1
Energy Saving (%)	11.15	3.4	11.45	10.9	0	7.45	3.85	4	15.65	3.9

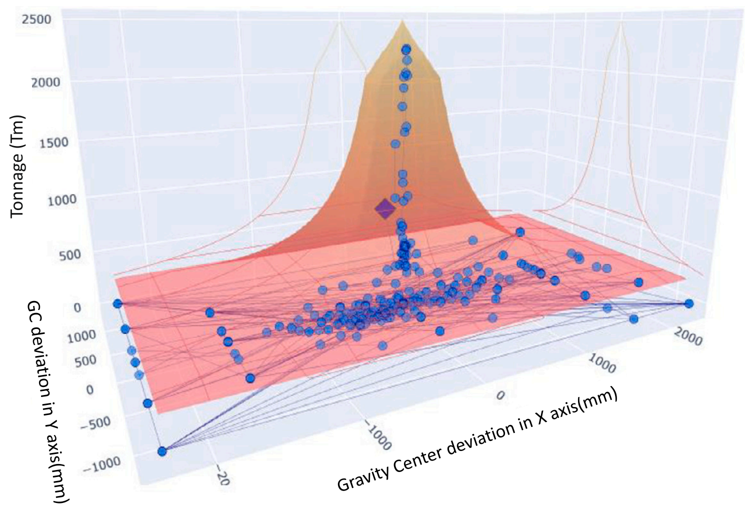

Fig. 9. Gravity Centre graph.

much energy the press consumes in one stroke. Then we adjust to the optimal counterbalance pressure and repeat the process. The percentage of savings is obtained directly with both values of consumption.

Table 3 shows the results obtained. We can see that of the 10 car body parts that are manufactured, only 1 was configured correctly, that is, item 5. Therefore by carrying out these corrections, 7.18% of consumption has been saved (Fig. 8).

6.2. Adjustment/tonnage

Our monitoring system of the press virtual gravity centre through the sensors of the Tonnage, detected a part that was being manufactured with a weight up to 2300 T, as seen in Fig. 9, an unusual load that had not been recorded previously and that was generating unnecessary energy consumption. We checked it and found out the following events: the part produced was the roof of the Ford Transit van in its large version 10 and therefore one of the largest forming dies available in the plant is used to manufacture this part.

It was shocking at first because a simple geometry car part should not cause problems unless something unusual happened, but everything seemed normal. So after making some research to figure out what could have caused this event, we realized that the die set was changed from one line to another, that is, new parameters had been set up in the press.

Fig. 10. Car body part - roof.

Table 4
Working parameters comparison.

Process parameters	PRE	POST
Tonnage (T)	2292	1618
Counterbalance (bar)	7.4	7.4
Slide reg. (mm)	1371.5	1373.5
Energy (kWh)	416	359

Comparing working parameters from one line to another we found out that the tonnage data monitoring was around 1500 tones. So try-out jobs were organized to modify parameters to optimize the process. With the amount of effort reduced while maintaining the quality of the part, we can say that the less effort made in the cycle, the lower the energy consumption will be made by the press. Table 4 shows the measured values before and after the in situ adjustment.

Here we can see that the tonnage has been reduced by about 700 tons by modifying the height of the regulation by 2 mm and the energy consumption in one hour of work has been reduced by 57 kWh, that is, by **13.7% energy savings.**

$$\Delta h = 2 \text{ mm} \;\rightarrow\; \Delta T = 700 \text{ Tm} \;\rightarrow\; \Delta E = 57 \text{ kWh}$$

7. Conclusion

This paper proposes an $I3oT$ framework for press energy saving based on the C360 criterion. The main drawback solved by this framework is the variability of the parameters of the stamping process and, therefore, the dependence on the human factor for its readjustment during the production process. These modifications that are made day by day in the plant are beyond the control of the managers because when there is a shift change at work the different line managers will apply their different techniques based on their experience to carry out the production required by the company. The objective of the operators is to guarantee production, even if the parameters used may not be the most optimal ones from an energy point of view. In this article, several algorithms are presented to calculate the optimal value based on the current status of the press and when comparing them with the set values configured by the operators, it is found that they are not optimal. In the case of the correction of the counterbalance pressure, a saving of 7.18% is obtained while with the corrections of the tonnage, a saving of 13.7% has been obtained. As future work, we propose implement this framework in all the presses in the factory in order to try to eliminate the human factor when carrying out the adjustment of analyzed parameters. Moreover, once all the energy data is monitored and analyzed, next step will be to develop a Smart Grid of the Press Shop based on the production schedule to optimize the energy supply.

CRediT authorship contribution statement

Ivan Peinado-Asensi: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicolás Montés:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Eduardo García:** Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request and with permission of Ford Motor Company. Data generated or analyzed during this study are not available due to legal policies of this research. Data were used under license for the current study, and so are not publicly available.

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