Energy efficiency optimisation in industrial processes: Integral decision support tool

Iñigo Bonilla-Campos[a,b,*], Nerea Nieto[a], Luis del Portillo-Valdes[b]

[a] *IK4-Ikerlan Technology Research Centre, Energy Storage and Management Area. P J.M. Arizmendiarrieta, 2. 20500 Arrasate-Mondragn, Spain.*
[b] *University of the Basque Country, UPV-EHU Faculty of Engineering of Bilbao Plaza Ingeniero Torres Quevedo s/n 48013 Bilbao, Spain.*

Abstract

Nowadays, assessing and improving energy efficiency in manufacturing processes is a crucial issue to become competitive. Besides, there are high margins of technical energy efficiency improvement for practically each sector and kind of industry. However, the margins of economic benefit or investment costs are not clearly defined. In order to get closer to these technical values many Energy Efficiency Measures (EEM) and tools to asses them have been proposed in bibliography. In this sense, the research effort has been mainly focused on the electric systems and the industrial continuous thermal processes. The electric processes are easier to manage than the thermal ones, and the continuous thermal processes have been widely assessed due to the higher absolute savings in comparison with the non-continuous processes. For these reasons, an efficiency gap in the non-continuous thermal processes has been originated. Despite the existence of many EEMs for each type of process, to fit an EEM to a specific process is a complicated task due to the different characteristic and restrictions of each specific manufacturing process. Due to the complexity of the non-continuous processes each measure has to be deeply analysed. For this purpose, this work presents an integral decision support tool to assess on the implementation of EEMs in non-continuous thermal processes. Once different possible EEMs are identified for a specific process, this tool allows to analyse the possible synergies that may be created among them and their impact on other parts of the process line. As a result, by means of this tool, the optimum solution or combination of solutions is determined in order to reach the highest levels of energy efficiency. In the case study used to present the integral decision support tool, a key EEM is projected, the introduction of a waste heat recovery system. However, the sizing of this system, and thus, its impact on the overall energy efficiency depend on its possible combination with other EEMs previously identified. By means of the tool, several packages of EEM are analysed for the specific case study with energy consumption reductions around 21% to 50%.

Keywords: energy efficiency measures, optimisation tool, process manufacturing, decision-making process, keyword

1. Introduction

The manufacturing sector is one of the biggest energy consumers in the world. The European Commission, through negotiation among the Commission, the European Parliament and the Council, has endorsed an indicative target of 32.5% energy savings for Europe's consumption by 2030 [1]. The new target of 32.5% will boost the industrial competitiveness, create jobs, reduce energy bills, help tackle energy poverty and improve air quality. Success in this aspect will depend largely on industrial energy efficiency, particularly on energy efficiency of energy-intensive industries.

In the non-ferrous metal sector, to which this study belongs, there is a high technical potential for reducing the sector energy consumption in a 22% with the current technology status [2]. However, only a 5.5% of the solutions returns the investment in less than two years. This means that, from the total technical potential for energy consumption reduction, only a quarter of the solutions returns the investment in less than two years. The difference between the theoretical technical potential and the economically viable one is called the energy gap [3, 4]. This gap can be reduced by improving energy management practices or increasing the

*Corresponding author
Email address: ibonilla@ikerlan.com (Iñigo Bonilla-Campos)

technical potential[5, 6]. The proposed work intends to address both issues: increasing the potential due to synergies among measures, and improving the management practices for the EEM evaluation. In the previous developed work [IE18 and SEEP18/RSER19] several solutions were identified for a heat treatment process, and one of them was deeply analysed: a waste heat recovery system. However, the proposed payback period was higher than two years. Besides, some possibilities of solution optimisation were identified. In this sense, the aim of this paper is to present an integral decision support tool that allows to select the best combination of solutions considering different criteria (from economic to environmental criteria). In the paper, the tool is used for the optimisation of the waste heat recovery system mentioned above by considering further EEMs.

The tool is based on a methodology for energy modelling of industrial processes and plants by simulation, and it eases the decision-making process [7] with reference to the most financially attractive option in energy efficiency improvement. This paper describes the analysis of different strategies to handle the energy efficiency of the process. The results show the energy efficiency potential of the different process modifications and include a detailed description of the sizing of the optimised waste heat recovery system. The paper is structured as follows [Background or literature review, Methodology: Analysis and Optimisation process, Results, Conclusions, and Discussions].

2. Background

Energy management, digitalisation of the process and the introduction of EEM are trending topics both for industrial environment and for research teams in order to make the manufacturing process more competitive. In this sense, many methodologies are emerging to manage this digitalisation and the energy-and-material flows, with the consequent increase of energy efficiency in production [8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. These advances in obtaining and processing of data into useful information allow to acquire deeper knowledge of the manufacturing process. These data and information may be understood and analysed from diverse points of view.

Understanding the entire manufacturing process as a unique system seems to be the best option in order to take total control of the energy-and-material flows [8]. Not only does this point of view see the energy flow data and plant information as a whole, but also integrates production, ecological and economic considerations. This holistic view links the relation among data series. One branch of the proposed holistic methodologies cover from building envelope energy to energy consumption processes [18]. When the manufacturing process requires high amounts of energy (Energy Intensive Industry (EII)) the building envelope may be set aside. In this case, the methodologies focus on the manufacturing process, the main energy consumer. The total control and knowledge of the EII processes is indispensable to achieve objectives such as improving the energy efficiency or inserting renewable energy sources [19]. A holistic multi-level and multi-scale analysis perspective allows to select the fittest EEM for the entire system [16]. The multi-level analysis covers the value chain, the process chain, the process and the specific device while the multi-scale covers the operating scale (seconds-minutes), the tactical scale (hours-days) and the strategic scale (months-years) [16]. The modern manufacturing process has highly dynamic energy patterns [14]. The modifications of the process, the substitution of the devices or the introduction of EEM may affect the other processes (of the value chain) upstream and downstream. This only could be properly analysed from this holistic point of view. Compared to the isolated analysis of processes, highlighting the dependencies among the different energy systems helps to identify further saving potentials and synergies for the optimisation of the manufacturing process.

The EEMs for the optimisation of the manufacturing process act in different scales. In the lowest scale the optimisation is achieved by modifying the device (operative-technological scale) [20, 21] or modifying the manner of working of the process (operative scale). In the upper scale (tactical scale), the process is optimised by adapting the production planning and scheduling, modifying the energy source mix [14, 22] or replacing this energy source with recovered energy [23]. In the highest scale (strategic scale) actions may be considered to change the scope of the entire plant, such as the product specialisation among factories [18].The strategic scale may affect the plant or process design stage. The plant and process design is an integral part of any product development process. The decisions taken at this stage account for the majority of the financial and environmental cost of a product [17]. Therefore, the energy efficiency potential (conditioned by the financial-economic impact) of a manufacturing process will be determined by this phase [18]. Many research teams propose to work in the process and device optimisation level [10, 12, 24, 25] to, then, extend the optimisation process to the whole manufacturing process (value chain level). Traditionally, decisions are made based upon intuition and experience, sometimes with the support of spreadsheet tools. These approaches can be risky and are unnecessary in decision making today[7]. With the new paradigm of process digitalisation [26] a new level of data acquisition is emerging. High amounts of data may be collected and processed. These amounts of data allow the operators and managers to foresee events; providing the creation of predictive maintenance strategies [27], and proposing scheduling or operation modifications; reducing the energy consumption [28].

An indispensable part of the optimisation task is to process and understand this database. The data are used to generate models to represent the real manufacturing process in virtual environments. These models may describe the energy behaviour of the system. The energy modelling is a powerful technique for analysing manufacturing systems, evaluating the impact of system changes, and for making informed decisions [29, 30, 31]. Thiede et al. [8] propose four main alternatives of methodological approaches: statics calculations, fuzzy logic, artificial neural networks and simulation. The energy modelling by simulation of the process is the most adapted technique for a specific manufacturing system [8, 32]. This methodological approach may be easily adapted to the uncertainties or the high variability of the non-continuous manufacturing processes [33]. The energy modelling by simulation allows to optimise the process and to identify the hidden gaps during the process.

However, there is a lack of decision support tools to assess this optimisation and identification [34]. Therefore, such a tool has been developed for the optimisation of a non-continuous energy intensive manufacturing process based on energy modelling by simulation. The models represent the dynamic systems of the process and replicate real working from a tactical and operative point of view. This work includes deep analysis of EEMs and the optimisation of these EEMs. This optimisation covers from the analysis of operative variables to the tactical and scheduling modifications in order to achieve the best working method. It is focused on the assessment of a technological energy efficiency measure, a waste heat recovery system, and how it is affected by the other EEMs. This waste heat recovery system will frame the optimisation, which means, the recovery system must be sized according to the level of optimisation of the process. Several synergies among measures are identified by this integral analysis.

3. Case Study

3.1. Aluminium die casting

As it was introduced before; a specific process from a manufacturing industry has been analysed. The heat treatment process of a real low pressure aluminium die casting. This process consists of three main sub-processes: the solution heat treatment furnace, the quenching stage and the ageing heat treatment furnace. The holistic analysis covers all the energy streams of these processes. Each furnace has its respective conditions of time and temperature, which correspond to the T6 heat treatment process for aluminium alloys [35]. The main energy and material flows for the production line selected for this case study are represented in Figure 1. The most crucial sub-process is the solution one, as the time and temperature conditions must be accurately tracked to assure the correct grain transformation. The ageing sub-process, apart from being essential, allows variations in the time-temperature conditions. These times in which the parts must remain at the specifics temperatures are referred as Solution Time Temperature State (STTS) and Ageing Time Temperature State (ATTS). The current values of STTS and ATTS are considered 100%;

The main characteristics of the heat treatment process are outlined below. The process is a non-continuous process; the input is variable in batch format; besides, it stops at weekends. As a first step, the parts are introduced by batches (packs of steel baskets) into the solution furnace; after that, the baskets are quenched, and then, they are subjected to the ageing process. The processes are divided in zone-stages: 9 stages, 1 stages and 7 stages respectively. There is an internal door between the first and second stage of the solution furnace. The process is manually commanded to start the introduction of batches in the solution furnace, then, it works automatically. Both solution and ageing heat treatment processes are fed by natural gas (NG) fired burners. The furnace chambers are under the ambient pressure to avoid hot air leaks.

3.2. The Heat Exchanger System (HES)

As introduced in previous works [tus referencias], the proposed heat exchanger recovers the energy [36, 23] from the exhaust gases of the solution process and directs the energy to the ageing process. The flue gases are directed from the stack collector to the heat exchanger, where it transfers its thermal energy. This recovery system is based on heat pipe technology [37]. A heat pipe transfers thermal energy passively from a hot to a cold stream through a boiling condensation cycle inside a hermetically sealed metal tube. In this way, heat from the hot area can be transferred very efficiently to a cold part of the pipe. The heat exchanger is fed, at the cold side, by the exhaust gases of the ageing process. The nominal characteristics of design are the following: hot section flow rate; 1580 kg/h, cold section flow rate; 1802 kg/h, hot section entry temperature (solution exhaust gases); 450°C, hot section exit temperature (solution exhaust gases); 259°C, cold section entry temperature; 145°C and exhaust exit temperature; 324°C. The nominal heat recovered for the unit is 93 kW and the total heat provided to the ageing furnace is 154kW (room temperature 25C). However, these numbers may be affected when further EEMs are considered, which will directly impact on the size of the waste heat recovery system, thus, in the following section the methodology to determine the final solution is explained.

The Heat Pipe Heat Exchanger (HPHE) is split in two sections: the cold section and the hot section. Each section works independently from each other; however, they are related by means of the energy efficiency of the HES. If an EEM reduces the mass flow of the hot section (solution exhaust gases), and, consequently, reduces the total energy, this section must be re-sized to this new feature, making a reduction of capital expenditures (CapEx) cost possible. This reduction in mass flow affects the cold section, which will require a new configuration (size and/or nominal working parameters). In these scenarios (baseline, HES and other EEM) the characteristics of the hot section are determined by the solution operating mode, meanwhile the characteristics of the cold section can be selected within a range. The main cold section characteristics are the mass flow and the output temperature. In this case, the output temperature is intended to keep the same value as the original design (around 330 °C). Therefore, the design value of the mass flow of the cold section is bounded by the availability of hot section mass flow. The control of this cold mass flow is determined by the requirements of the ageing process. The cold flow rate is controlled so as not to exceed the process temperature. The results of the preheating phase (when there are no parts in the furnace) must be analysed individually, so as not to distort those of the stationary stage.

4. Methodology

First, the developments presented in previous works [tus referencias] are introduced in order to frame the current optimisation and sizing process. Then, the macro strategy selected to increase the energy efficiency

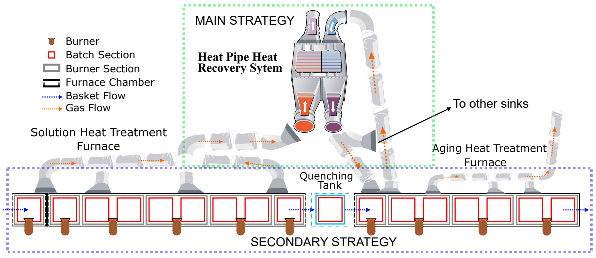

Figure 1: Main material and energy flows of the processes. Strategic course of action.

is explained. In the third part, the energy, production, ecological and economic assessment is explained. Finally, the EEMs characteristics are introduced and the optimisation process is guided.

4.1. Research framework

This research is framed within a methodology for holistic energy modelling by simulation of thermal industrial processes. This methodology has been developed to identify, quantify and evaluate EEMs in the process (SELF-CITATION). This methodology aims to identify limitations of the measure, synergies among processes or sub-processes and to predict the energy operation of the selected process within the entire plant. The manufacturing process is a continuous process, so, the modelling approach follows a continuous system adapted to a non-continuous production [38]. This energy modelling returns all the energy flows involved in the process. Besides, it reproduces the time-temperature profile of the parts, allowing to evaluate the impact of process parameter modifications. The process is then virtually reproduced by specific process models (production, ecological and economic models), developed and implanted in MatLab software (SELFCITATION). After the verification and validation of the models, by means of data captured from in plant sensorization, the process is virtually adapted to the available working factors.

4.2. Action plan strategies

The main strategy to improve the energy efficiency of the heat treatment process is to implant a waste heat recovery system (upper rectangle in Figure 1). This recovery system consists on two proposals: to re-feed the stack gases of the second process to the entry of the heat exchanger's cold part, and to modulate the heat exchanger to be able to provide heat to other sinks as a function of the requirements and needs. The optimisation system is oriented to both, the sizing of the HES and the evaluation of heat supply to other sinks, such as heating, combustion air preheating or drying systems.

The secondary strategy (lower rectangle in Figure 1) is to implant modifications in the working parameters of the heat treatment process in order to modify the system. The factor modifications are oriented to reduce the energy requirements or to change the energy flows related to the heat exchanger so as to reduce the cost (the size) of the heat exchanger. Besides, some measures are able to modify the characteristics of the heat treatment. The production analysis takes into account these variations in order to guarantee that the treated parts reach the required conditions.

4.3. Energy, production, economic and ecological assessment

The energy and material flows, obtained as simulation result, are the principal outputs of the modelling [31]. The energy modelling allows, for a preliminary production input, to reproduce the real working of the process for this specific input. This production input may be post modified in order to optimise this production system.

For the energy assessment, all energy-material flows, such as burners consumption (individually), stack gases streams, lateral heat losses, air combustion flows, air infiltration flows and production mass output and input, are controlled and known. Besides, other working parameters are ad-hoc measured or obtained in order to take control of the process. The main parameters taken into account are: the internal chamber pressure, the area of infiltration, the basket fixture characteristics, the air combustion temperature, the internal door state, the ambient temperature and the parts initial temperature. These factors and parameters may be then modified for the process and recovery system optimisation. The main restrictions of the processes are tracked by the parts temperature control. The parts must remain, at least, the established time (STTS and ATTS), at the specific temperature in order to ensure the structural change.

The production assessment consists on evaluating how the production restrictions or conditions are affected by the diverse working parameters. As a result, some interesting production variables are logged, such as the time that the process spent to reach the process temperature or how much time each batch remains at this critical temperature (STTS and ATTS). These variables are mainly dependent on the batches input (quantity of mass introduction and frequency) which are commanded by the tactical and scheduling strategies. In this sense, other non-production parameter modifications may affect this critical variables. Therefore, a specific measure may reduce the total time of production (for a specific production set) or increase the total production (for a specific working time). All these variables and conditions are analysed in the production assessment and subsequently economically valued in the economic assessment.

The ecological assessment takes into account the principal pollutants and greenhouse gases that are a consequence of the production process. The particles reproduced by the models, analysed in this assessment, are carbon dioxide (CO_2) and nitrogen oxides (NO_x). These are produced during NG burning at the burners. This particle production mainly depends on the total power, the excess air and the temperature of the combustion air. The analysis of the CO_2 generated is made from two points of view: the one directly related to the combustion of the NG and the one related to the life cycle of this gas: generation, transmission and distribution [39]. The NO_x generation is approached by the performance graphs of the burners worksheets as a function of the instant power. The NO_x emission data[1] is given for specific nominal conditions (such as percentage of O_2 or the temperature of the firing chamber) and adapted later to the process conditions (such as real O_2% or real combustion temperature).

The economic assessment gives a monetary value to all the previous outputs and, also, provides an approach of the investment cost, the operation&maintenance cost and the implantation cost. The energy efficiency increase of the process is translated into three factors: energy, time and production. A specific EEM may affect the three factors. These three factors may be linked with the production specific consumption (in terms of energy for quantity of production [kWh/ton$_{\text{produced}}$]). The economic valorisation of the energy savings is directly translated into economic value by means of the cost[2] of the energy used (NG in Spain). The economic valorisation of the time and production factors depend on the strategic and tactical flexibility to modify the production. However, some approaches are taken into account to evaluate these production benefits. The ecological valorisation is made according to the cost of the CO_2 European emissions allowance[3]. Both principal savings are represented as S_{NG} [€] and S_{CO_2}[€]

[1] From ppm to kg http://www.faberburner.com/resource-center/conversion-charts/emissions-conversions-calculator/

[2] Energy price per gigajoule [€/GJ]: https://ec.europa.eu/eurostat/tgm/refreshTableAction.do?tab=table&plugin=1&pcode=ten00118&language=en

[3] Carbon price per ton from [€/ton]: https://markets.businessinsider.com/commodities/co2-emissionsrechte

In front of the savings, the operational expenditures (OpEx), the CapEx and the preliminary activities expenditures (C_{pa}) derived from the EEM are proposed (also in €). The OpEx is split in; parasitic load due to any power consumption as a part of the EEM, the operating and maintenance cost (O&M) and the personnel cost. If any operating saving is incurred, it will be accounted for in the OpEx term. The CapEx correspond to the technological investment (perishable and device) and to the installation, and the C_{pa} correspond to previous researching works. The C_{pa} may be saved if the same measure is proposed for another production line, process or factory.

As a final conclusion of this assessment three economic indicators are approached: Levelized Energy Efficiency Cost (LEEC), Simple Payback Period (SPP) and the Return Of Investment (ROI) for each measure. The LEEC indicator proposed by Chiaroni et al. [40], correlates the energy savings that can be achieved through the implementation of an energy efficiency technology and the total costs incurred throughout the entire life cycle of the technology, e.g., initial investments, (O&M), disposal costs. Therefore, this indicator returns the real cost of the energy provided by this implementation. The SPP accounts for the time required to recover the cost of an investment, with zero interest rate, while the ROI measures the gain or loss generated by an investment in relation to the amount of money invested (for a specific period).

$$SPP = \sum_{t=0}^{SPP} CF_t \geq 0 \tag{1}$$

$$LEEC_T = \frac{\sum_{t=0}^{T}(C_{pa} + CapEx_t + OpEx_t)}{\sum_{t=0}^{T} TES_t} \tag{2}$$

$$ROI_t = \frac{CF_t}{(C_{pa} + CapEx_t + OpEx_t)} \tag{3}$$

and:

$$CF = (S_{NG} + S_{CO_2}) - (C_{pa} + CapEx + OpEx) \tag{4}$$

where CF [€] considers net cash inflows during the period t [years]. The term Total Energy Saved (TES) represents the energy savings generated by the EEM to keep the same levels of production.

The EEMs in industry yield a number of outcomes beyond energy reduction and cost savings; for instance, productivity increase, product quality improvement, waste reduction and maintenance labour reductions [41]. But these measures could also generate societal benefits and utility benefits. Evidence suggests that these benefits are a non-trivial component of the total benefits of energy efficiency [42]. However, the uncertainty of the non-energy benefits estimates must be correctly addressed to account for the EEM full value.

4.4. Energy Efficiency action plans

Some course of action was identified as a consequence of the in-depth analysis of the processes, the comprehension of the modus operandi and the behaviour of the devices. These measures were analysed individually and as a support to the first strategy measure: the recovery system.

The first branch of action affects the production way and the process restrictions. In this sense, the following measures are proposed: the removal of anomalies on the entry time, the basket load increase (if possible) and the reduction of the time of the process [43, 35]. The weight batch increment depends on the part typology. The last measure (process time reduction) affects directly to the STTS and ATTS. As it was explained, the parts must remain, at least, a specific time at the temperature conditions. However, there is evidence that the time selected may be overestimated [44, 35, 43]. Therefore, some limited time reductions should not modify the expected mechanical characteristic.

The second branch works on the surroundings of the processes without modifying the process characteristics or the production plan. In order to reduce the infiltration flow the following measures are suggested: the reduction of the infiltration area (due to the non-perfect closure of the doors, grooves near the burners, of gaps at the conveyor rollers) and the control of the internal pressure. Besides, to increase the combustion air temperature of the burners is proposed. This heat may come from low heat recovery systems in the plant or from the excess heat recovered at the HES system. The main purpose of this proposal is to assess the energy behaviour and the environmental impact of both processes. Besides, some economic supposition has been selected for the analysis. The heat requirements (of the air preheating) are analysed individually for each situation.

The third course of action acts on specific devices. This procedure covers measures, such as the implantation of an internal door to separate the first and the second stage; to avoid cold intrusions to the heated parts, and the substitution of the steel basket fixture with a lighter one [45, 46]; around 40% of the energy absorbed by the load is for heating the steel basket. In this sense, with fibre-carbon composites, the energy reduction may reach values around 80% by maintaining the basket properties. This energy reduction is the comparison between the average for heating the current steel baskets

	Acro.	Range	Characteristics	CapEx	OpEx	CPa
Baseline HES	HES	-	A 93 kW heat recover from Solution furnace to Ageing furnace.	35300	50	0
Zero Anomalies	ZA	half-full	The entry time period remains constant, without alterations nor interruptions.	35300	50	500
Load Increase	LI	2'5%-8%	A greater number of pieces is introduced.	35300	50	2500
Time Reduction	TR	5%-15%	The entry time period is reduced the proposed values.	35300	50	4000
Infiltration Area	IA	33%-66%	The infiltration area is blocked or reduced the proposed values.	36300	100	1000
Internal Pressure	IP	18%-75%	The pressure is adjusted to reduce the pressure difference with the ambient	34300	100	1000
Combustion Air	CA	150°C-330°C	The combustion air temperature is increased.	45300	250	3000
Internal Door	ID	-	The inner door starts to work regularly.	35800	60	1000
Fixture	Fx	-	The fixture of the baskets changes to fiber carbon composites.	60300	-50	5000

Table 1: Individual EEM proposed and analysed for preliminary assessment.

and the proposed new baskets for the nominal process temperature (from 25°C to 540°C and to 160°C).

All these measures are jointly reproduced with the HES measure. The proposed EEMs have been individually analysed by the proposed tool for the whole range of application. This range of application has been defined in order reasonable production and device capacity characteristics. The cost of the EEMs increases nonlinearly according to the range increment as adaptation to the real behaviour of the engineering costs. The EEM ranges of implantation have to fulfil a series of overall requirements, the most restrictive ones are commented below:

- STTS and ATTS: These time values must not be reduced more than 20% and 25% respectively (regarding the current times).
- Basket Load: The load of each basket must not exceed the 150% (regarding the maximum current load)
- Internal Pressure: The internal pressure of each section must not be near (5 Pas) to exterior pressures.
- Air Temperatures: The solution and ageing furnace convection air temperature (after the flame) must not exceed 600° C and 200° C.
- Annual production: The annual production is fixed by the factory strategical plan.

In line with these considerations, it is presented a series of proposed measures (for determined implementation values) with the aim of addressing the preliminary assessment. Two values of implementation range are assessed (low and high) in order to acquire an in-depth knowledge of the behaviour. The proposed EEM, the acronym, the characteristics, the range analysed and the suggested costs are summarised in Table 1. The costs represented in Table 1 refer to the low range.

4.5. Optimisation: combinatorial assessment

The last part of this work aims to select the best combination of measures to optimise the selected factor. The optimised factor may be economic, energetic, ecological or a production factor, such as maximum energy reduction, shortest SPP, highest ROI, CO_2 emissions, etc., or a weighted combination of them. The optimisation process is approached as an heuristic iterative simulation process, due to the high variability of the production inputs and the high dynamism of the manufacturing process. Some measures may have high impact on a specific control parameter. This impact may be incremented or reduced by a combinatorial package of measures. Each proposed package corresponds with five different measures selected to optimise the required factor. The heuristic iterative procedure is required to get closer to the relative optimum. This optimisation process analyses and selects the combinations and proposes new configurations by modifying a EEM parameter. As it was explained before, this work reproduces the real modus operandi of the manufacturing process for a specific period. Therefore, a relevant period must be selected in order to accept or refuse a course of actions. For this reason, any modification may be analysed and verified individually, hindering and drawing out the optimisation process. This generates high amount of data with high computational work. On the basis of the preliminary results (subsection 5.1) the selection of measures for each package may be directed to save time and computational work. This guidance is done by the analysis of the preliminary results, where the impact is individually assessed. The ranges proposed in Section 4.4 may be exceeded in the combinatorial packages due to synergies among measures.

Five "packages" of EEM are obtained in order to reach the next five different goals: minimisation of the SPP, maximisation of energy reduction, minimisation of the HES sizing, maximisation of the production and the conservation of the current STTS and ATTS. The last one is the most conservative goal, the process is minimally affected. Both the process STTS and ATTS, the internal pressure, the NO_x production, the production plan (number of treated parts) and the basket composition remain invariable.

5. Results

In this section, the EEMs proposed in 4.4 and 4.5 Sections are evaluated by means of the tool. As a first step, the baseline (current method of operating) is established and the HES proposal, just as it has been proposed in the project summary, is evaluated. After that, the secondary strategy proposals are evaluated individually. The last part analyses the EEM packages proposed in Section 4.5.

The analysed factors cover all the scopes assessed: energy, environmental, production and economics. The energy assessment includes the overall energy consumption of the heat treatment (weighted regarding the HES). The environmental outlook is represented by the CO_2 generation. The NO_x generation is only discussed for the measures which modify the combustion characteristics (CA). The STTS and ATTS (time[4] that the parts stay at the process conditions), the total time to treat the parts, the production rate and the HES working load represent the modus operandi of the process. The selected economic indicators, derived from these scenarios and the cost assumption are the following: the economic savings, the SPP and the LEEC and ROI indicators for three-year period. Some results are confronted to the HES measure factors (100%) in order to keep the confidentiality of the production data.

The HES workload factor provides only the average HES workload in relation to its nominal design (Section 3.2). In this sense, it is also weighted according to the HES baseline in order to ease the understanding of the factor. Some measures modify the design, therefore, the workload factor will be referred to the new HES design. The new design capacity is commented individually for each case.

5.1. Preliminary results: Main strategy

As it was introduced before, this tool not only provides energy or economic results of the suggested measures, but also allows to know and to adopt the suitable manner of working of the processes and devices in the new situation. In this case study, the way of providing heat to the parts in the ageing furnace changes. The energy flows previously provided by the NG combustion at the burners partially disappear, and a new energy flow becomes the main heat supply. Therefore, a new configuration setting with preliminary piping construction works has been considered and adapted to the models. This configuration is designed to provide all the heat to raise the temperature of the parts to the required level. In practice, the first burner stops working, meanwhile the others only have to provide the lateral and infiltration heat losses.

The analysis of the main EEM proposed, the HES measure, brings the results presented below. The overall energy consumption of the process decreases 13'6%. However, this EEM only affects the ageing process, which generates a relative energy efficiency improvement of 89'5%, according to BL. This implies that the ageing process is only consuming a 10'5% of the baseline values. These energy savings represent 448 MWh / year. From now on, the relative energy efficiency is according to HES values. Emissions are reduced in the same proportion as well as consumption, around 13'6%. The main characteristics of the way of working remain invariable. The HES works at 73% of its capacity, it means that during some periods the energy of the solution gases is not being recovered. The HES reduces the workload in order not to overheat the parts. This EEM returns a SPP of 28'4 months. The LEEC attributed to the measure is 27'6€/MWh for the first three years. However, it is quickly reduced to 21'7€/MWh for a six-year evaluation period. The ROI behaves in the same way, reaching values of 28% and 149% for three and six-year periods respectively. Bearing in mind the economic factors, this implies that the cash flow becomes positive at 27 months (the investment is already recovered), while for the third year, all the investment and 28 % more of the amount invested would be back in the coffers. During this period, the price of the energy used would have been equivalent to 27€/MWh.

5.2. Basic EEM results

After this minimal modification for adapting the HES, in order to optimise the correct utilisation of the recovered heat, all the proposed EEMs are assessed by means of the proposed tool. The results are summarised in Table 2. Each EEM affects in a different way to the production and energy behaviour. Therefore, the impact on the economic indicators is different. As it was shown, the greatest energy reduction is obtained by the main strategic measure: the heat pipe HES. In addition, other proposals stand out providing great savings (Consumption Overall in Table 2) .

[4] Outliers are excluded

	Range	Energy Consumption Overall [%]	Eco CO_2 [%] Emissions	Process Way of Working Restrictions [%] STTS	ATTS	Total time [%]	Production Ratio [%]	HES load [%]	Economic Indicators Savings [k€/month]	SPP [months]	LEEC 3y [€/MWh]	ROI 3y [%]
BL	-	113.6	113.6	100	100	100	100	-	-	-	-	-
HES	-	100	100	100	100	100	100	73	1.293	28.4	27.6	25.4
ZA	half	99	99	99.7	99.6	98.6	101.4	73.9	1.383	26.8	26.1	32.5
ZA	full	98.4	98.4	99.2	99.1	97.7	102.4	74.8	1.444	26	25.4	36.1
LI	2.5%	98.1	98.1	99.7	99.6	97.6	102.5	73.6	1.476	26.5	25.8	34.2
LI	8%	94.1	94.1	99.5	99.1	92.6	108	75	1.852	22.4	21.8	58.4
TR	5%	96.7	96.7	94.5	94.3	95.1	105.1	76.2	1.603	25.3	24.6	40.4
TR	15%	90.3	90.3	83.5	83.4	85.4	117.2	83	2.212	18.4	18.1	91.4
IA	33%	93.4	93.4	100.3	99.1	100	100	79.8	1.915	20.6	20.5	68.6
IA	66%	86.9	86.9	100.8	98.1	100	100	87	2.530	17.2	17.9	92.9
IP	18%	98.7	98.7	100	99.7	100	100	75.3	1.417	26.8	26.4	31.2
IP	75%	96.3	96.3	100.1	99.2	100	100	81.6	1.644	22.3	22.3	55.4
CA	150 °C	94.3	94.3	101	99.9	100	100	72.8	1.831	30.6	30.1	15
CA	330 °C	86.9	86.9	102.4	99.8	100	100	72.9	2.532	26.9	26.7	29.6
ID	-	96.9	96.9	105.1	99.7	100	100	74.7	1.590	24.1	23.6	46.9
Fx	-	92.7	92.7	103	103	100	100	52	1.989	32	30.7	12.8

Table 2: Main energy, production, ecological and economic results for the basic EEM.

5.2.1. *Zero Anomalies*

This EEM is a very conservative EEM which only affects to the operational tracking of the tactical plan. The energy savings of the "full" implementation are rather low (53 MWh/year) for the analysed period. However, this measure has moderate improvements for the process total time and for the production rate without affecting the process restrictions. Both solution and ageing relative energy efficiency's are affected by this EEM, which increase 1% and 3% according to HES processes efficiencies. The HES workload slightly increases. During the anomalies the batch stays more time than programmed in the stage. In this "extra" time the HES works at low power since the batch has already reached the temperature. If this time is eliminated, and a new load is introduced, the HES returns to the nominal load. Despite the low energy savings, the economic results show acceptable improvements due to the very low costs of this measure.

5.2.2. *Load Increase*

The increase of the load of each basket will allow to produce the same production with less batches, reducing the time the furnace are working and, therefore, theirs consumption. The EEM shows moderate energy savings: 64-194 MWh/year according to the Table 2 range. The time restrictions remain practically invariable. The HES workload also suffers a slight increase. The HES needs to work more time at nominal due to the load (weight of treated parts) has increased. From the economic point of view, all economic factors increase while increasing the load, however, this increase is delimited by the theoretical basket fixture and parts shapes and the tactical plan. The manufacturing process may present some bottleneck which prevents the load increase.

5.2.3. *Time Reduction*

The main characteristic of this EEM is that the time the parts stay in the furnace is reduced. Consequently, the time which the parts remain at the critical restrictions is reduced (STTS and ATTS). The specific energy efficiency of each process is increased. Thus, the overall consumption is reduced, reaching high values of energy savings (107-319 MWh/year according to the Table 2 range). Besides, both the total time and the production ratio is directly improved. The HES working load is also improved by similar reasons of ZA measure. On the one hand, this kind of measure shows one of the best economic results, due to the low initial investment, but on the other, the risk induced to the mechanical properties must be assessed. The tactical plan is practically not critically involved and may be solved with a minor stock modification.

5.2.4. *Infiltration Area*

This measure shows great results without modifying the process modus operandi nor the tactical plan. The highest energy saving is obtained with this EEM (430 MWh/year according to the Table 2 upper range). The HES workload analysis of the Infiltration Area reduction also shows interesting results. This measure reduces the infiltration flow, so also reduces the energy of the exhaust gases forcing a re-sizing of the HES. The hot section of the HPHE must to be adapted to the new exhaust gases flows. The available energy of the solution fumes is reduced by 34'3% for the upper range of area reduction. The enthalpy of the exhaust gases almost remains unchanged, due to the fact that the process temperature characteristics are not modified. As consequence, the cold part is also adapted. The final CapEx reduction is already shown in the Table 1. The energy efficiency of the solution process suffers strongly rise whereas the ageing efficiency falls. Despite the fact the reduction of the ageing infiltration area increases the efficiency (the ageing demand come down), the heat availability of the HES also come downs. The final ageing balance is negative due to the fact that burners have to provide heat which previously was provided by the larger HES. The overall balance is very positive due to the weight of the solution process in the overall consumption is much greater. The size of new HES shown in Table 1 is 77kW and 61kW for the low and high range. The HES workload, which is referred to this new HES size, shows high working loads due to the reduction of the transferred nominal power. Thus, even a "low" loads, the HES is nearer to the nominal load than in other measures. This measure shows the best economic results, with short SPPs and high ROIs. A more accurate sealed supposes higher expenditures and maintenance cost.

5.2.5. Internal Pressure

As the previous measure, this measure affects on the furnaces infiltration flow. This EEM also presents the same conclusions than the Internal Area measure regarding to energy, ecological, production and HES considerations. For the analysed ranges (Table 1) the HES size is reduced 4% and 17%. The economic indicators depends on the proposed cost and take into account the operation cost of the pressure control. A more accurate pressure control will supposes high expenditures and operation cost.

5.2.6. Combustion Air

This kind of measure presents high energy savings and improves (or maintains) the process way of working (STTS and ATTS). The emissions are, practically, directly correlated with the energy consumption. However, this EEM considerably increases the NO_x generation. The process goes from a specific generation of 0.14 $kg_{NO_x}/ton_{TreatedPart}$ to 0.16 $kg_{NO_x}/ton_{TreatedPart}$ even with the NO_x reduction associated to the energy consumption reduction. From the economic point of view, this measures has the handicap of the high initial expenditures. Therefore, the economic results worsen the initial ones (HES). For this EEM, some devices and O&M costs have been supposed to obtain a comparative point of view. However, the real cost analysis related to this kind of measure will depend on the characteristics of the demanded heat to reach the selected preheating temperature. The energy demanded for the 150°C preheating scenario is 28'2 kW and 3'4 kW to solution and ageing respectively. The average combustion air mass flows for this scenario are around 860kg/hour and 100kg/hour. These ranges of power and mass flow may be provided in average by the HES reducing the expenditures considerably. However, this evaluation requires a posterior and in-depth analysis. The economic impact on the maximum contracted power is not taken for economic account.

5.2.7. Internal Door

This measure, which proposes to isolate the first from second stage (Solution furnace), avoids cold flow incursions in heated parts, improving the solution restriction (STTS) around 5%. For the energy point of view, this EEM shows moderate energy saving (100MWh/year), which is generated by a better (more efficient) working way of the burners. The obtained economic results improve those of the HES baseline. This measure brings great production-economic results for the future combination with other EEMs.

5.2.8. Fixture

This measure affects radically on the energy demand of the batches. Each batch requires certain amount of energy to reach the process temperature. This energy demand is split in basket contribution and part contribution. The part contribution is indispensable to the process. However, the basket contribution is unnecessary for the process. To this aim a totally substitution of the current steel baskets by other made of other material. To reduce the heat capacity of these baskets supposes high benefit both in energy savings (240MWh/year), environmental aspects; 7% of NO_x and CO_2 reduction, time restriction improvements; around 3% and other energy and non-energy related benefits derived from the high weight reduction (roller conveyors, baskets transport, etc.). In contrast to these benefits, this EEM entail high expenditures. and the HES workload is seriously affected. The hot supply of the HPHE practically remains invariable however the cold side demand is drastically reduced. Almost 50% of the HES potential is not used. This behaviour provides opportunities to future combination of measures or to future searches of energy sinks. The economic indicators suffer the handicap of the entire substitution, showing the worst economic results of the preliminary assessment. If the substitution

	Measure package & Implementation Range				
	I	II	III	IV	V
ZA	✗	✗	✗	✗	✓ full
LI	✓ 7%	✗	✗	✓ 11%	✗
TR	✓ 20%	✓ 23%	✗	✓ 22,5%	✓ 4,5%
IA	✓ 43%	✓ 66%	✓ 66%	✗	✓ 66%
IP	✗	✗	✓ 55%	✗	✗
CA	✗	✓ 330C	✗	✗	✗
ID	✓ yes	✗	✓ yes	✓ yes	✓ yes
Fx	✗	✓ yes	✓ yes	✓ yes	✗
CapEx	34000	94600	68400	72600	44500
OpEx	110	200	60	-40	110
CPa	8500	13900	8000	12500	6300

Table 3: Range and cost for the obtained combinatorial packages.

is extended during the time, to the extent the old baskets break, the amortisation grows quickly.

In contrast to energy savings results, some measures affect the current production restrictions of the process, modifying the STTS-ATTS parameters. Measures which limit the time restrictions can be combined with measures that improve the time restrictions to create energetic-economic synergies by decreasing the risk of defective production.

5.3. *Combinatorial results*

On the basis of the presented previous results a new assessment is proposed. The combination of different measures generates synergies in the process which may go beyond the improvement of the individual EEM. On the contrary, some combination of measures may cushion the overall effects. The final "packages" with their respective measures selection, the range and the costs are summarised in Table 3. The final results of the combinatorial packages are summarised in Table 4. The results of each combination are explained in the following sections.

5.3.1. *SPP optimum*

This optimum, on the basis of the measures costs assumption, plays with the EEM range due to the set out non-linearly costs. Besides, measures with high CapEx are penalised. The measures obtained are the following: the Load Increase, the Time Reduction, the Infiltration Area reduction and the Internal Door. However, there are several solutions that reach similar values (months) of SPP. This optimum is totally dependent on the monetary weights attributed to the costs. Modifications or updating on the costs will determine the measures combination and/or the range of these. For the costs proposed scenario and the selected measures this optimum shows a SPP of 12'5 months and moderates energy savings of 764 MWh/y. The solution hot fumes are reduced around 24% (due to IA and ID measures), therefore, the HES size is reduced to the 76% of its size. This CapEx saving is already accounted in Table 3. The HES workload maintains a good performance of 88'6% for the new size. The time restrictions parameters reach critical theoretical values with reductions of 20% of the solution time and 25% of the ageing time. These new conditions, despite being supported by research, must be confirmed prior to implementation. The production ratio increase may be managed by two ways: accumulation of stock before the Heat Treatment Process or increasing the production rate before the Heat Treatment Process. This last way will modify the factory tactical plan. The accumulation of stock may represent a room/place availability problem that must be analysed.

5.3.2. *Energy saving optimum*

This optimum sacrifices the SPP and the NO_x production in order to reduce the NG consumption to the maximum. The four optimal measures selected are: the Time Reduction, the Fixture change, Combustion Air preheater and the Infiltration Area reduction. As no economic nor process-restriction indicators have been chosen for this optimum, all measures are selected in their maximum range. Only the "Time Reduction range" is delimited to secure theoretical values of ATTS and STTS. This optimum shows the highest energy savings of 1865 MWh/y at the expense of the SPP, which grows to 21 months. Both solution and ageing efficiency increases considerably (around 70% and 50% according to HES furnace energy efficiency). The HES size is reduced to the 66% while the average workload is about 75% of its new nominal design.

5.3.3. *HES size optimum*

In this theoretical scenario the size of the HES is reduced. This is achieved by reducing the ageing requirements (making the ageing process more efficient). In the same way, if the solution process becomes more efficient the exhausted gases which feed the HES are reduced. Thus, the HES size reaches a reduction of 40%. The new nominal duty of the unit will be 56kW while the nominal heat provided to the ageing will decrease to 92kW. As consequence of these modifications the STTS greatly increases. The ATTS shows improvement in a lesser extend. From the economic point of view this package improves around 6 months the SPP of the HES measure. These results are similar to the results of the second package, however, the initial investment is clearly lower.

	Energy	Eco	Process Way of Working					Economic Indicators			
	Consumption Overall [%]	CO_2 [%] Emissions	Time Restrictions [%] STTS	ATTS	Total time [%]	Production Ratio [%]	HES load [%]	Savings [€/month]	SPP [months]	LEEC 3y [€/MWh]	ROI 3y %
BL	113.6	113.6	100	100	100	100	-	-	-	-	-
HES	**100**	**100**	**100**	**100**	**100**	**100**	73	1.293	28.4	27.6	25.4
I	76.8	76.8	80.3	75.8	75.2	133	88.6	3495	12.6	12.8	170.8
II	56.9	56.9	79.9	77.4	77.5	129	75.7	5378	21	20.7	67.3
III	74.7	74.7	110.9	102.3	100	100	72.6	3687	21.1	20.5	69
IV	70.6	70.6	82	79.1	79	140.5	66.5	4081	21.1	20.4	69.8
V	82.6	82.6	99.9	92.6	93.4	107.1	89.8	2942	18.6	18.8	83.9

*The values in bold are those that have been taken as a basis for the comparison / weighting.

Table 4: Results of the combinatorial assessment EEM.

5.3.4. Production maximum

The number of parts processed is increased in this package. Apparently, the measures which individually increase the production should be obtained as the selection process of this package. However, the Zero Anomalies, which increased the production directly, has been substituted by the Internal Door measure. This apparently incongruity is analysed below. The package measures consists of: load increase, time reduction, internal door, and fixture change measures. In this scenario must to be emphasised that the Fixture and the Internal Door measures have selected due to they provide reductions in both process restriction times. Therefore, in combination with the Time Reduction measure allows to increase the productivity more points. This synergy between measures allows to transform the increase in the ”time restriction” provided by the Fixture and Internal Door measure into production increase by means of the reduction of process time through the Time Reduction measure. There are two ways to increase the production: to increase the workload, and to reduce the production time. This is reflected by the total time (hours to treat the all batches); which shows a reduction of 21% in comparison with the reference time (BL), and by the production factor; which shows an increase of 38’3%. The energy consumption reduction decrease strongly in comparison with other packages (savings of 1400MWh/year). The HES power shows higher values (average of 100kW of provided power) due the fact that a higher production rate implies higher demands in the furnaces. However, the HES workload remains low, around 62%, due to the nominal power (153kW) is not modified. This package shows acceptable values in the economic indicators, improving in 7 months the HES baseline SPP. If there is an urgent need to increase the production, it may be better solution than installing another heat treatment line. This package explores this situation.

5.3.5. Conservative escenario

This package ensures that the critical conditions of the solution process remain unchanged. This package is not an optimal one, but it fulfills a series of fixed requirements while trying to optimise energy savings. Therefore, after fixing some criteria, the factor optimised is the ”energy saving”. The conditions of the ageing process are assured by the analytically assessment of the HES and by the high flexibility of the restrictions. The conditions of the solution process are assured by keeping the current working ”time restriction”. The parts remain the same time at critical temperature than in the current working mode. Other conditions, such as the heating temperature profile and the internal pressure remain similar to those of the baseline (BL). Within the prescribed limitations, this package brings moderated energy and ecological outputs. In spite of this moderated energy savings, the economic results are very good due to the low investment required for this package. However, the monthly savings are low in comparison with other packages.

6. Conclusions

The obtained energy and productive results remain invariable for the analysed scenarios, however, the economic interpretation of these results will depend on the economic assumptions and on the production or factory specific requirements. This tool allows to make posterior sensitivity analysis with economic variations. In this sense, a sensitivity analysis for the entire proposed range for the Load Increase, Time Reduction, Internal Area, Internal Pressure and Combustion Air EEM is presented. The Figure 2 compiles these results. The range with minor return period depends on the expenditures and on the energy savings and show different behaviour for each analysed measures. These behaviours may show diverse trends, such as parabolic or strictly decreasing.

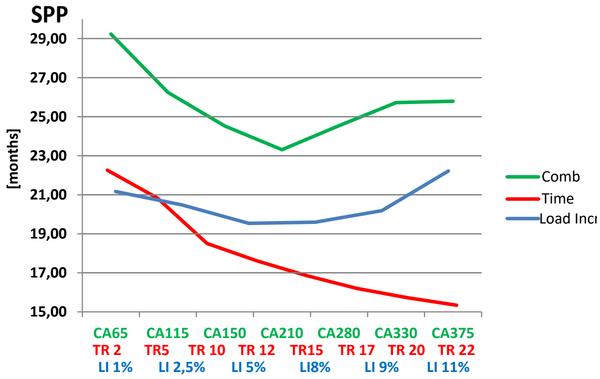

Figure 2: Simple Payback Period for the EEM entire range.

For this analysis some conditions, some economic assumptions and a wide variety of measures were selected in order to obtain some specific optimums. The results show that there are high margins of improve in manifold ways. The potential may reach up to 50% of the current energy consumption. This tool allows, based on some premises, to assess with a high degree of knowledge the processes and the entire production line. This case study is oriented to the analysis of the main measure, the HES measures, and how other changes in the process, other modus operandi and the tactical decisions affect to the HPHE design, to the energy behaviour and to the production plan. Besides, this tool opens the door to a new ad-hoc optimisation process generated by the industrial user, easing the transference of process knowledge, the adaptation of tactical criteria and bringing the decision-maker closer to the manufacturing process. This tool integrates different levels of analysis (economic, envirommental, production and energy) with different levels of decision making (operation, tactical and strategic).

7. Discussion and future work

The assumptions of the economic assessment are based on reasonable hypothesis and data obtained by the public reports. However, both the accuracy of the expenditures as well as the cost trends for the range of implementation may vary in a real scenario. Beyond this hypothetical inaccuracies, the objective of this research is to prepare the tool for future EEM, processes and plants. The enregy modelling is validated by historical data validation in diverse conditions, which presents an acceptable theoretical medium-low degree of subjectivity [47]. Strong modifications of the initial scenario may distance the energy real behaviour. Nevertheless, we have not found evidence to think that the energy behaviour of the process may change substantially.

The proposed solutions and packages are obtained by heuristic analysis. The energy behaviour interaction among measures and range of measures generates an infinity of scenarios. The analysis of these scenarios supposes working time and computational power. This opens an opportunity to automatise the optimum selection and expand the criteria of the decision making process. The considered ideas as so far are two. First, to automatise the heuristic process by an iterative procedure and log the results to make "results maps". These maps will allow an approach, outside the simulation process, for optimisation or approximation to the optimum. Second, obtain solutions by weighted objectives and analyse how affects this weighting with a sensitive analysis. In addition, a generation of a user interface has been proposed. This interface will allow the interaction of employees not related to the tool to obtain conclusions and a better management of the process (operational decision). The interface will also facilitate the decision making process for tactical or strategic decisions EEM.

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