Energy- and Exergy-Based Analysis for Reducing Energy Demand in Heat Processes for Aluminum Casting

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In this paper, energy- and exergy-based analysis is used to analyze a factory with high energy demand for the production of aluminum discs. The analysis is focused on heat processes that take place in a melting furnace, a casting machine, a heat treatment oven, and a drying oven. Energy and exergy efficiencies are computed to assess the room for the improvement of the energy efficiency processes. The analysis shows that a large amount of energy is lost due to heat losses to the environment, and solutions for reducing energy demand and emissions have been identified. Instead of changing the equipment of a factory, significant improvements and consequent reduction of fossil fuels consumption can be obtained by increasing the thermal insulation of some components and by means of waste heat recovery performed by heat exchangers, with a consequent energy demand reduction of 15%.
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1 Introduction

The increase of primary energy costs and environmental concerns, and the reduction of fossil fuels availability have led to a new approach to energy: as regard to processes, if in the past the focus was more on performance, that is on productivity, nowadays the focus is shifting toward efficiency, that is, on reducing the quantity of energy required by a process. The concern about world energy consumption, and environmental emissions that impact on climate changes, has led to a series of standards [1–5] addressed to regulate the use of energy. These standards [1–5] illustrate the issues that need to be pointed out in the energy analysis of an industrial process; however, there is a lack of specific information on how to determine process efficiency, that is, whether a process requires more energy than that necessary. Just measuring the energy consumed by a process does not give information on its efficiency. There are processes that, for their nature, require a great amount of energy and processes that consume sizable amount of energy because they are designed by considering energetic aspects only partially.

Thermodynamics provides the tools for investigating how energy is exploited and, consequently, for determining the room for improvement of systems and processes. Energy, entropy, and exergy are well-known thermodynamic concepts that provide the foundations for a correct analysis of the effectiveness of an industrial process. We refer to Ref. [6] for the general definitions and engineering interpretations of these concepts. Here, we just recall that according to the first law of thermodynamics, energy is a property that can be measured through a weight process, can be transferred between systems by means of interactions, and is always conserved. Actual processes are not reversible, thus their effect cannot be canceled, and this can be described by means of the entropy balance. Like energy, also entropy is additive and it can be transferred between systems depending on the type of interaction, but it is not conserved. For an isolated system, entropy increases until it reaches the maximum value compatible with the constraints provided by energy and chemical species conservation. The simplest types of interactions a system may undergo are work, heat, and bulk flow: work involves energy transfer without transfer of entropy and chemical species, heat involves energy and entropy transfer without transfer of chemical species, and bulk flow involves transfer of energy, entropy, and chemical species. More complex processes require more sophisticated thermodynamic models (see, e.g., [7]) that have been developed to describe various nonequilibrium types of interactions such as thermodiffusion, thermoelectricity, and so on.

From the concepts of energy and entropy, exergy can be defined. Exergy represents the maximum work that can be obtained in a given environment and under specified constraints from a system in a given initial state or from a given heat or bulk flow. For example, for a given initial state, it can be computed by carrying the system to the dead state where its temperature is equal to that of the environment temperature. Systems not in equilibrium with the environment can be exploited for producing work. Differently from energy, exergy is destroyed in irreversible processes: the greatest the exergy rate destroyed, the highest is the room for improving its efficiency. As explained in Refs. [8,9], energy- and exergy-based analysis may focus on an entire process or just on a component of the system depending on the chosen level of analysis: for example, manufacturing activities can be organized in devices, lines, facilities, multifactory systems, enterprise, and supply chains [9]. Examples of exergy analyses are available for geothermal power plants [10,11], solar energy systems [10,12–14], and thermal processes [15–19].

An energy and exergy analysis of a drying process in a ceramic industry is presented in Ref. [20]. The exergy destruction rate of an industrial AC electric-arc furnace is investigated in Ref. [16], where it is found that the energy efficiency is 96%, although the exergy efficiency is 55% only.

An aluminum melting furnace in a die-casting plant is analyzed in Refs. [17,18]: the energy and exergy efficiencies are estimated equal to 10% and 6%, respectively, and since the process entailed an exergy destruction rate of 50%, it is suggested to preheat ingots and to recovery heat from combustion air. A heat exchanger network in a complex natural gas refinery is investigated in Ref. [21] for heat waste recovery. Several cogeneration plants are analyzed and compared in Refs. [20,22–24] with a focus on the parameters affecting efficiency. A multifactory system and enterprise/global supply chain are analyzed in Ref. [25]: an optimization of the energy flow in different industries located in Japan is proposed with the aim to reduce the energy demand of the country. It is stated that interconnecting the various industries or plants would entail a reduction of 90% of the oil consumption.

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It emerges that the reduction of energy demand can be achieved in two ways: by designing more efficient processes and by using all the amount of energy introduced in a process (for example, with waste heat recovery). However, exergy can also be used in economics [26–29], chemical [30–33], and environmental [34,35] analysis. It also plays an important role as a possible basis for allocation methods in cogeneration and hybrid power and materials processing in the context of developing fair energy policies and regulations aimed at promoting higher overall primary energy efficiencies in regional areas [36].

In this paper, energy and exergy analysis is used to investigate efficiency improvements in a factory with a high energy demand. The factory produces discs made of aluminum. The production consists of several heat processes described in Sec. 2. Heat is obtained from burning natural gas and by the Joule effect from electrical energy; to satisfy the energy demand, there is also a gas natural fired cogeneration facility that supplies heat and electricity. The aim of the analysis has been to compute energy and exergy efficiency of the different processes and to identify solutions to reduce the energy demand and the discharge of recoverable energy in the environment. A constraint in the analysis has been to maintain unchanged the technology currently in use because the change in technology would involve huge investments of money and time to get used to it. Thus, the possible solutions have been researched among those with an immediate effect and among the less expensive ones.

2 System Overview

The factory under study produces aluminum discs through the process shown in Fig. 1 that consists in seven steps, accomplished in seven different plant areas. For each step, one or more utilities are used. This study focuses on heat exchanges, mainly.

The production process starts in the melting aluminum area (step 1), where aluminum ingots and aluminum shavings are melted in two different types of furnaces: three furnaces melt ingots, and two furnaces melt shavings. Then, the melted aluminum is transported to the casting process area (step 2) where it undergoes a die-casting process in 25 utilities; these latter are made of an oven and a mold: the liquid aluminum is poured into the oven where it is maintained at constant temperature until it is injected into the mold; the injection is performed by pressurizing the molten aluminum inside the oven with compressed air. In the mold, liquid aluminum cools and solidifies. After that, the discs are sent to the heat treatment area (step 3) for a heat treatment process in order to give them the required mechanical properties. In this area, the discs are heated in a oven, cooled in a water basin, then heated again in a second oven. Then, the discs are sent to the mechanical machining area (step 4), where computer numerical control (CNC) machines perform roughing and finishing operations. Successively, the discs are washed in the washing area (step 5) to remove residuals from their surface upon immersion in a series of basins containing water and detergents. In step 6, the discs are painted in the painting area that consists of a series of ovens: in the degassing-oven the discs are heated to remove any possible bubble inside them, in the powder-oven the paint on the discs is fixed, and in the last oven heating allows evaporation of the solvents contained in the paint. At the end of the production process (step 7), the discs are stored.

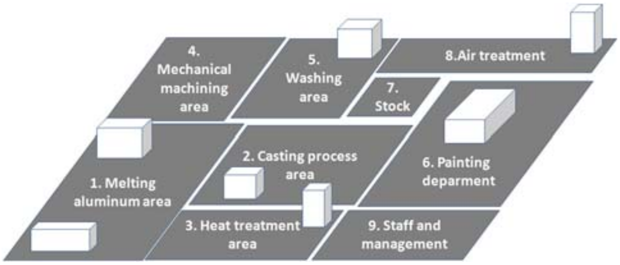

Fig. 1 Illustration of the factory: according to Ref. [8], the rectangles represent the facilities or areas, and for each of them one or more utilities are shown

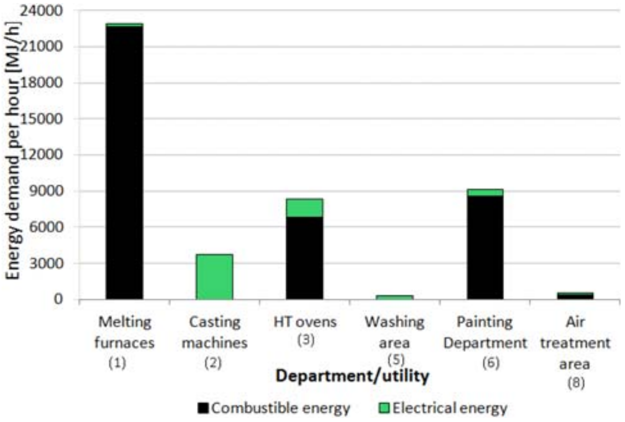

Fig. 2 Factory energy consumption

Figure 2 shows the energy consumption in the different areas of the factory: the energy sources, natural gas, and electrical energy are distinguished. Electrical energy is used to handle products and mechanical components in the melting aluminum area, in the heat treatment area, and in the painting department. Electrical heating is used to maintain the liquid aluminum at work temperature in the ovens of the casting process area.

In this study, four utilities are analyzed: the furnace that melts ingots, the oven of the casting machines, the heat treatment oven, and the drying oven. For the casting machine area, only the process in the oven is analyzed because here the majority of energy is consumed. In the heat treatment area, a great amount of energy is converted into heat necessary to heat the discs, whereas a negligible quantity of electrical energy is supplied to the pumps of the water basin. In the mechanical-machining area, there are not significant heat exchanges. The amount of energy used in the washing area and in the air-treatment area is negligible. Most of energy supplied to the painting area results from natural gas combustion.

3 Analysis Method

In this section, equations used in the study are reported.

3.1 Energy and Entropy Balances.

As stated in Sec. 1, a system may undergo work, heat, and bulk flow interactions. Depending on the interaction, transfer of energy $E^{\leftarrow}$, exergy $Ex^{\leftarrow}$, mass $m^{\leftarrow}$, and entropy $S^{\leftarrow}$ may occur (the $^{\leftarrow}$ means positive if inward).

The general balance equations that describe the rates of change of the energy E and the entropy S of a system that undergoes continuous work, heat, and bulk flow interactions are

$$\frac{dE}{dt} = \dot{W}^{\leftarrow} + \dot{Q}_T^{\leftarrow} + \dot{Q}_{T_o}^{\leftarrow} + \dot{m}^{\leftarrow}(h_1 - h_2) \tag{1}$$

$$\frac{dS}{dt} = \frac{\dot{Q}_T^{\leftarrow}}{T} + \frac{\dot{Q}_{T_o}^{\leftarrow}}{T_o} + \dot{m}^{\leftarrow}(s_1 - s_2) + \dot{S}_{\mathrm{irr}} \tag{2}$$

where the changes of kinetic and potential energy have been neglected, $\dot{m}^{\leftarrow}$ is the rate of mass transfer (positive if inward), $\dot{W}^{\leftarrow}$ is the rate of energy transfer via work interactions, $\dot{Q}_T^{\leftarrow}$ and $\dot{Q}_{T_o}^{\leftarrow}$ are the rates of energy transfer by heat interactions at temperatures T

and T_o, respectively, h_1, s_1 and h_2, s_2 are the specific enthalpies and entropies of the inlet and outlet bulk flow streams, respectively, and $\dot{S}_{\rm irr}$ is the rate of entropy generation by irreversibility. The rates of energy and entropy change, $\mathrm{d}E/\mathrm{d}t$ and $\mathrm{d}S/\mathrm{d}t$, can be either positive, negative, or zero (for a steady-state process), while entropy generation by irreversibility $\dot{S}_{\rm irr}$ is positive in irreversible processes (zero only in reversible processes). Since entropy generation is an unwanted effect, processes are generally designed trying to minimize it compatibly with the economic considerations.

The linear combination of Eqs. (1) and (2) obtained by multiplying Eq. (2) by the environmental temperature T_o and subtracting the result from Eq. (1) yields the exergy balance equation

$$\frac{\mathrm{d}(E - T_o S)}{\mathrm{d}t} = \dot{W}^{\leftarrow} + \dot{Q}_T^{\leftarrow}\left(1 - \frac{T_o}{T}\right) + \dot{m}^{\leftarrow}[(h_1 - h_2) - T_o(s_1 - s_2)] - T_o\dot{S}_{\rm irr} \tag{3}$$

Depending on the substance, the changes $\mathrm{d}E/\mathrm{d}t$ and $\mathrm{d}S/\mathrm{d}t$ in the energy and entropy of the system, and the differences $h_2 - h_1$ and $s_2 - s_1$ in the mass specific enthalpies and entropies of the inlet and outlet bulk flows are computed with either the model of solid or incompressible fluid, the perfect gas model, or the two-phase model as follows.

For a substance that can be modeled as a solid or incompressible fluid, the equations are

$$\frac{\mathrm{d}E}{\mathrm{d}t} = mc\frac{\mathrm{d}T}{\mathrm{d}t} \tag{4}$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = m\frac{c}{T}\frac{\mathrm{d}T}{\mathrm{d}t} \tag{5}$$

$$h_2 - h_1 = c(T_2 - T_1) + (p_2 - p_1)/\rho \tag{6}$$

$$s_2 - s_1 = c\,\ln\frac{T_2}{T_1} \tag{7}$$

where m is the mass, c is the mass specific heat capacity, ρ is the density, and T is the temperature. For a substance that can be modeled as an ideal gas, the specific internal energy $u_{\rm fg}$, enthalpy $h_{\rm fg}$, and entropy $s_{\rm fg}$ of vaporization must be considered.

For a substance that is two-phase condensing at constant pressure, the equations are

$$\frac{\mathrm{d}E}{\mathrm{d}t} = mu_{\rm gf}\frac{\mathrm{d}x}{\mathrm{d}t} \tag{8}$$

$$\frac{\mathrm{d}S}{\mathrm{d}t} = ms_{\rm gf}\frac{\mathrm{d}x}{\mathrm{d}t} \tag{9}$$

$$h_2 - h_1 = (x_2 - x_1)h_{\rm gf} \tag{10}$$

$$s_2 - s_1 = (x_2 - x_1)s_{\rm gf} \tag{11}$$

where x is the vapor mass fraction and $u_{\rm gf}$, $h_{\rm gf}$, and $s_{\rm gf}$ are the specific internal energy, enthalpy, and entropy of condensation.

For a fuel input and the corresponding output of products of combustion at atmospheric pressure (assuming complete combustion and neglecting mixing and condensation effects), the approximate equations are

$$\dot{m}^{\leftarrow}(h_{\rm fuel} - h_{\rm comb.prod.}) = \dot{m}^{\leftarrow}_{\rm fuel}\mathrm{LHV} \tag{12}$$

$$\dot{m}^{\leftarrow}(s_{\rm fuel} - s_{\rm comb.prod.}) \approx 0 \tag{13}$$

where LHV is the specific lower heating value of the fuel and we have adopted the approximation (see Table 31.7 of Ref. [6]) that for most hydrocarbons the enthalpy Δh^o and Gibbs free energy Δg^o of combustion differ by no more than ±2.5% and, therefore, the entropy of combustion Δs^o can be neglected and the fuel exergy (which is given by $-\Delta g^o$) can be approximate for many practical purposes by the LHV (i.e., $-\Delta g^o \approx -\Delta h^o$). Under these approximations, the exergy content of a fuel is equal to its energy content, i.e.,

$$\dot{E}x_{\rm fuel} \approx \dot{E}_{\rm fuel} \approx \dot{m}^{\leftarrow}_{\rm fuel}\mathrm{LHV} \tag{14}$$

Energy efficiency $\eta_{\rm I}$ and exergy (or second-law) efficiency $\eta_{\rm II}$ for a given process that produces some useful effects consuming some energy resources are defined as follows:

$$\eta_{\rm I} = \frac{\dot{E}_{\rm useful\ effects}}{\dot{E}_{\rm resources\ consumed}} \tag{15}$$

$$\eta_{\rm II} = \frac{\dot{E}x_{\rm useful\ effects}}{\dot{E}x_{\rm resources\ consumed}} \tag{16}$$

Different from other works in the literature, in this paper, energy efficiency and exergy efficiency are denoted with $\eta_{\rm I}$ and $\eta_{\rm II}$, instead of η and ψ.

3.2 Heat Transfer Analysis. The study has focused on heat loss $\dot{Q}_{\rm loss}$ through the utilities shell due to convection $\dot{Q}_{\rm conv}$, conduction $\dot{Q}_{\rm cond}$, radiation $\dot{Q}_{\rm rad}$, and thermal bridges $\dot{Q}_{\rm TB}$

$$\dot{Q}_{\rm loss} = \dot{Q}_{\rm conv} + \dot{Q}_{\rm rad} = \dot{Q}_{\rm cond} + \dot{Q}_{\rm TB} \tag{17}$$

where the energy loss $\dot{Q}_{\rm TB}$ due to thermal bridges has been computed according to Ref. [37].

Heat losses are estimated by using the following equations:

$$\dot{Q}_{\rm conv} = h_{\rm conv}A\,(T_{\rm surf} - T_0) \tag{18}$$

$$\dot{Q}_{\rm cond} = \frac{(T_{\rm in} - T_0)}{R}A \tag{19}$$

$$\dot{Q}_{\rm rad} = \sigma A\,\epsilon(T_{\rm surf}^4 - T_{sa}^4) \tag{20}$$

where $h_{\rm conv}$ is the convective heat transfer coefficient, A is the surface, $T_{\rm surf}$ is the shell mean temperature, T_0 is the temperature in the factory, $T_{\rm in}$ is the temperature inside the utilities, R is the shell thermal resistance, σ is the Stephan–Boltzmann constant, ε is the surface emissivity, and T_{sa} is the mean temperature of the surfaces in the factory. Heat transfer coefficients have been computed using standard correlations from Incropera [38].

3.3 Exergy Analysis. As seen in Eq. (3), the exergy balance equation requires the choice of a reference environmental temperature T_o. In our study, we adopt $T_o = T_0$ the temperature in the factory.

For work interactions, exergy is equal to the work itself $\dot{E}x_W = \dot{W}$, while for a heat interaction at temperature T, it is defined as

$$\dot{E}x_{Q,T} = \dot{Q}_T\left(1 - \frac{T_o}{T}\right) \tag{21}$$

For steady bulk flow interactions, the difference between outlet and inlet specific exergy is

$$ex_2 - ex_1 = (h_2 - h_1) - T_o(s_2 - s_1) \tag{22}$$

where h is the specific enthalpy and s is the specific entropy. Thus, for flow of an incompressible fluid (or solid)

$$ex_2 - ex_1 = c(T_2 - T_1) - T_o c\ln\frac{T_2}{T_1} \tag{23}$$

of an ideal gas

$$ex_2 - ex_1 = c_p(T_2 - T_1) - T_o c_p \ln\frac{T_2}{T_1} + \frac{T_o R_u}{M}\ln\frac{p_2}{p_1} \tag{24}$$

and of a two-phase boiling or condensing fluid

$$ex_2 - ex_1 = (x_2 - x_1)(h_{\mathrm{fg}} - T_o\, s_{\mathrm{fg}}) \tag{25}$$

Thus, for example, for a steady-state heat exchanger, the energy and entropy balances yield

$$\dot{Q} = \dot{m}_h(h_{h,i} - h_{h,o}) = \dot{m}_c(h_{c,o} - h_{c,i}) \tag{26}$$

$$\dot{E}x_{\mathrm{loss}} = T_o\dot{S}_{\mathrm{irr}} = \dot{Q}\,T_o\left(\frac{s_{c,o} - s_{c,i}}{h_{c,o} - h_{c,i}} - \frac{s_{h,i} - s_{h,o}}{h_{h,i} - h_{h,o}}\right) \tag{27}$$

where subscripts i and o stand for inlet and outlet, and h and c for hot and cold stream.

4 Assumptions and Input Data

Input data provided by the factory are reported in Tables 1 and 2. In Table 2, the variability of fuel consumption is highlighted. To verify the computing, the conservation of mass and energy has been verified. Fuel consumption has been calculated by summing process energy consumption and energy loss, and to verify the calculations and the assumptions made, it has been compared with that provided by the company and reported in Table 2.

Unless otherwise stated, the following assumptions have been made:

- All utilities operate at steady conditions. Start-up phase is neglected, since it amounts to a small fraction of the production time.
- With the exception of the air flow in the casting-machine, pressure is everywhere considered equal to atmospheric pressure $p_0 = 101.325$ kPa.
- Aluminum alloy and water are modeled as incompressible perfect solid/liquid: for the aluminum alloy, the specific heat is taken equal to $c_{as} = 0.838$ kJ/kg K and $c_{al} = 1.108$ kJ/kg K for the solid and liquid phases, respectively; for water specific heat $c_w = 4.2$ kJ/kg K is taken.
- The aluminum alloy considered liquefies at 886 K, and its fusion enthalpy is 431 kJ/kg.
- Air is modeled as a perfect gas with specific heats $c_p = 1.039$ kJ/kg K and $c_v = 0.7423$ kJ/kg K, and molecular mass M_m equal to 29 kmol/kg.
- Exhaust gas is treated as if it were air.
- Combustion is considered as a complete combustion.
- Natural gas LHV is 31.16 MJ/m^3.
- The reference temperature T_0 in the exergy analysis is assumed to be 298 K.
- Air entering the utilities is taken from the external environment at 285 K.
- Potential and kinetic energy variations are neglected.

Table 1 Process input data supplied by the company

Utility	Quantity	$\dot{m}$ (kg/h)	T_1 (K)	T_2 (K)
Melting furnace	Air (inlet)—exhaust gases (outlet)	4600	285	993
	Solid aluminum	1868	473	993
	Liquid aluminum	238	973	993
Casting machine	Air	20	285	993
	Liquid aluminum	468	983	993
Heat treatment oven	Air (inlet)—exhaust gases (outlet)	3000	285	808
	Discs heating (B)	1680	293	808
	Discs heating (C)	1680	353	418
Painting department	Air	4032	285	423
	Discs heating	9000	296	328
	Water evaporation	24	298	423

Table 2 Hourly energy consumptions provided by the factory

Utility	Energy consumption
Melting furnace	158–202 m^3/h (natural gas)
Casting machine	120 MJ/h (electricity)
Heat treatment oven	90–112 m^3/h (natural gas)
Drying oven	28–30 m^3/h (natural gas)

4.1 Heat Exchanger Performance. In the analysis, the effects of heat recovery performed by means of heat exchangers have been investigated.

As shown, for example, in Ref. [38], in a heat exchanger with two incompressible fluids, the maximum variation in temperature can be experienced by the fluid of lower thermal capacity rate $\dot{m}_c c_{\min}$. By considering an ideal counterflow heat exchanger of infinite length, the temperature $T_{c,o}$ of the cold fluid outlet is equal to the temperature $T_{h,i}$ of the hot fluid inlet. Then, the maximum heat flow $\dot{Q}_{\max}$ transferred is

$$\dot{Q}_{\max} = \dot{m}_c c_{\min}(T_{h,i} - T_{c,i}) \tag{28}$$

The efficiency ε of the heat exchanger is defined as the ratio of the actual heat transfer rate and the maximum heat transfer rate

$$\varepsilon = \frac{\dot{m}_c c_{p,c}(T_{c,o} - T_{c,i})}{\dot{Q}_{\max}} = \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{c,i}} \tag{29}$$

In this study, the heat exchanger efficiency ε has been assumed equal to 50%, a little lower than that of typical devices in the market. In this way, the model is in favor of safety.

5 Results and Discussion

In this section, energy and exergy efficiencies are computed for the furnace that melts aluminum ingots, the casting machine, the heat treatment oven, and the drying oven. The utilities are schematized in Fig. 3 where inward and outward are specified. Solutions for reducing the energy demand are also proposed and analyzed. Process data provided by the staff of the factory are reported in Table 1: since they were measured in different moments of the production and for different purposes, they are not correlated. For this, they have been used just to evaluate the validity of the calculations. To verify the reliability of assumptions and calculations, estimated fuel consumption have been compared with nominal values provided by the company.

5.1 Melting Furnace. The melting furnace is schematized in Fig. 3(*a*): it is composed of a loading chamber, a combustion chamber, and a waiting chamber. Before entering the combustion chamber, aluminum ingots are heated in the loading chamber by exhaust gases from the combustion chamber where natural gas is burned. When their temperature reaches 473 K, the ingots enter the combustion chamber where also liquid aluminum coming from another furnace is poured. As reported in Table 1, ingots and liquid aluminum enter the combustion chamber at different temperatures. When the aluminum in the combustion chamber reaches 993 K, it is poured in the waiting chamber from which, at regular time intervals, it is stapled to be transported to the utilities that follow in the process sequence.

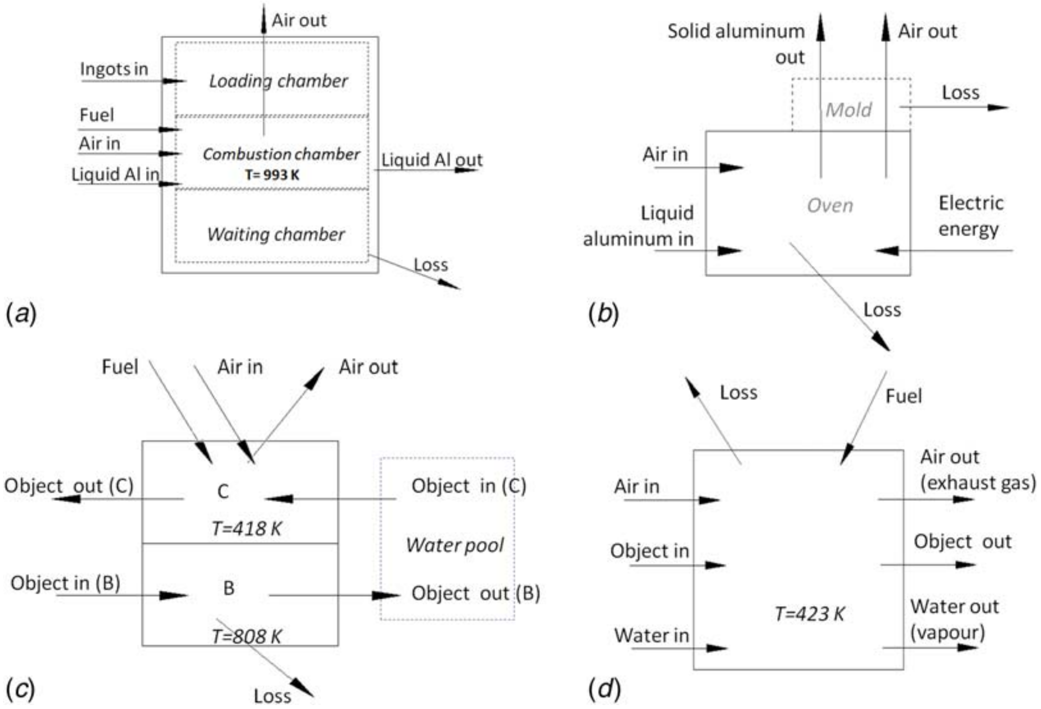

Fig. 3 Illustration of the utilities analyzed: (*a*) melting furnace, (*b*) casting machine, (*c*) heat treatment oven, and (*d*) drying oven

Energy and exergy efficiencies have been computed according to Equations (15) and (16) as

$$\eta_{\rm I} = \frac{\dot{E}_{\rm ingots} + \dot{E}_{\rm shavings}}{\dot{m}_{\rm fuel}{\rm LHV}} = 33\% \tag{30}$$

$$\eta_{\rm II} = \frac{\dot{E}x_{\rm ingots} + \dot{E}x_{\rm shavings}}{\dot{m}_{\rm fuel}{\rm LHV}} = 19\% \tag{31}$$

where $\dot{E}_{\rm ingots}$ and $\dot{E}x_{\rm ingots}$ refer to the heat provided to heat and liquefy the ingots, while $\dot{E}_{\rm shavings}$ and $\dot{E}x_{\rm shavings}$ refer to the heat provided to the liquid aluminum coming from the other furnace.

From Table 3, it emerges that about 52% of the available exergy is destroyed in the process; then, there is a great room for improvement. Since the exergy destruction for a steel production process in a AC electric arc furnace is only 44% [16], it could be stated that the exergy destruction may be due to the combustion. Also an alternative technology could be employed to perform this process but this goes beyond the scope of this study. Nevertheless, the efficiencies here determined are rather higher if compared to the ones calculated by Rosen and Lee [17]: for an aluminum melting furnace, it was found energy and exergy efficiencies equal to 10% and 6%, respectively. The difference can be due to the fact that here ingots are heated up to 473 K before entering the combustion chamber, while in the study performed by Rosen and Lee [17], ingots enter the combustion chamber at 298 K. The energy loss through the furnace shell is low: despite the average temperature of the furnace surface is 373 K, its area is of only 77 m^2; then, an improvement of the thermal resistance of the walls could lead to a limited reduction of the energy demand. The majority of energy from the natural gas combustion is transferred to air entering the combustion chamber and that exits the furnace with a high exergy content. Thus, for reducing the energy demand, energy contained in the outlet air should be transferred to inlet air by means of a heat exchanger: in this way, the temperature of the inlet air can be risen significantly.

For the computing of the inlet air temperature, it has been hypothesized that only 50% of the maximum heat flux is transferred to the inlet air. With this expedient, the inlet air temperature can be risen up to 379 K and, consequently, the difference in temperature becomes 614 K instead of 708 K. By increasing the inlet air temperature, energy η_I and exergy η_{II} efficiencies become 36% and 20%, respectively, and the energy is now allocated as shown in Fig. 4. The increasing of the inlet temperature determines a reduction of the fuel consumption of 15 m^3/h, that is, a reduction of the 8% of the current energy demand.

Table 3 Energy and exergy allocation for one melting furnace

	Energy per hour (MJ/h)	% of the inflow energy
Air	3385	57.7
Aluminum (ingots)	1947	33.2
Aluminum (liquid)	5	0.1
Surfaces loss	524	9.0
Total	5862	100.0
	Exergy per hour (MJ/h)	**% of the input exergy**
In	5862	
Out		
Air	1606	27.4
Aluminum (ingots)	1095	18.7
Aluminum (liquid)	4	0.1
Surface loss	102	1.7
Total	2807	47.9
Exergy destruction	3167	52.1

5.2 Casting Machine.

A model of the casting machine is sketched in Fig. 3(*b*): it is composed of an oven whose function is to maintain the aluminum at constant temperature by means of electrical resistances and a mold in which the aluminum is injected. As previously stated, only the oven has been analyzed because this part of the systems consumes the majority of the energy supplied to the utility.

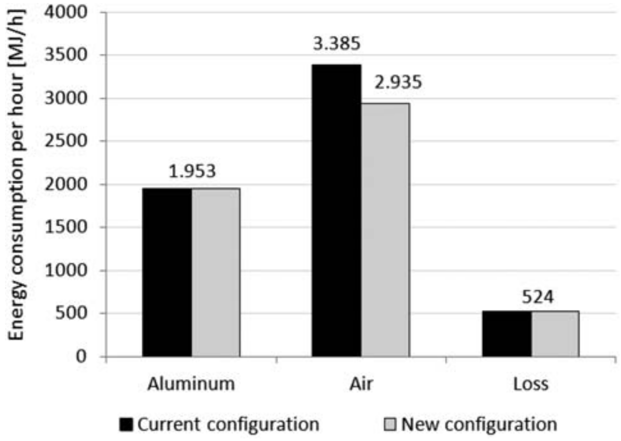

Fig. 4 Energy consumption distribution for the melting furnace

Table 4 Allocation of energy for one casting machine

	Energy per hour (MJ/h)	% of the input energy
Air	1.0	0.9
Aluminum	49	44.5
Loss	60	54.5
Total	110	100.0
	Exergy per hour (MJ/h)	% of the input exergy
In	110	
Out		
Air	1	0.9
Aluminum	48	43.6
Loss	20	18.1
Total	69	62.6
Exergy destruction	41	37.4

To compute the efficiency of the oven, it is necessary to describe some details of the casting process. Liquid aluminum is transported from the melting furnace to the casting machines by means of forklifts and this takes up to 3 min, with a consequent drop of its mean temperature from 993 K to 983 K. During the casting process, the opening of the oven occurs ten times per hour with an additional drop in temperature of about 10 K any time. Since the temperature of the air entering in the oven for its pressurization is 285 K, heat is transferred to it. Then, heat is provided to rise and maintain the aluminum in the oven at 993 K.

Energy and exergy efficiencies have been computed considering the heat necessary to maintain the liquid aluminum at 993 K

$$\eta_{\mathrm{I}} = \frac{\dot{E}_{\mathrm{all}}}{\dot{E}_{\mathrm{elec}}} = \frac{\dot{m}_{\mathrm{all}} c (T_2 - T_1) \dot{N}}{\dot{E}_{\mathrm{elec}}} = 45\% \tag{32}$$

$$\begin{aligned} \eta_{\mathrm{II}} &= \frac{\dot{Ex}_{\mathrm{all}}}{\dot{Ex}_{\mathrm{elec}}} \\ &= \frac{\dot{m}_{\mathrm{all}} c ((T_2 - T_1) - T_0 \ln (T_2/T_1)) \dot{N}}{\dot{Ex}_{\mathrm{elec}}} = 43\% \end{aligned} \tag{33}$$

where $\dot{N}$ is the number of times per hour that the drop in temperature occurs. The efficiencies η_{I} and η_{II} are rather similar because the difference in temperature is rather small (only 10 K); then, the variation of the entropy content $\ln(T_2/T_1)$ approaches 0.

From Table 4, it can be seen that about 37% of exergy entering the utility is destroyed in the process: this entails a margin for improvement. Since about 55% of the energy available is lost through the oven shell, it has been proposed to increase its thermal resistance. The oven shell is schematized in Fig. 5(*a*), where it emerges that there is not a layer that may offer great thermal insulation. Figure 5(*b*) shows the temperature measured on the oven surface, and it can be seen that the temperature of the oven shell surface is high. Since there are 25 casting machines, the energy loss in the casting department is of great entity. In the inner part of the oven, materials are in contact with liquid aluminum, then, only ceramic materials can be installed here, but their thermal resistance is weak. Then, it has been proposed to install a fibrous insulating material externally to the oven shell. Since only 15 cm of space was available, a layer of mineral wool of 10 cm thick of thermal conductivity equal to 0.07 W/mK (referred to the temperature measured on the oven shell) has been chosen. This expedient would entail a reduction of the energy demand from 110 MJ/h to 68 MJ/h, that is a reduction up to 38%, and an increase of the energy η_{I} and exergy η_{II} efficiency up to 62% and 60%, respectively. In Fig. 6, it can be seen that in the new configuration the majority of energy is exploited for heating the aluminum, while in the current configuration the majority of energy is lost through the oven surface.

5.3 Heat Treatment Oven. The utility in the heat treatment department is shown in Fig. 3(*c*): it is composed of an oven B at 808 K, an oven called C at 418 K, and a water basin. The discs coming from the casting department enter the oven B where their temperature is risen from 293 K up to 808 K, then they are immersed in a water basin where their temperature drops to 353 K, and finally they enter the oven C where they are heated again up to 418 K. Hot air heated in a combustion chamber is blown on the discs. A certain amount of air is transferred from oven B to oven C but, given that the mass rate transferred is unknown, ovens B and C are analyzed as a single unit.

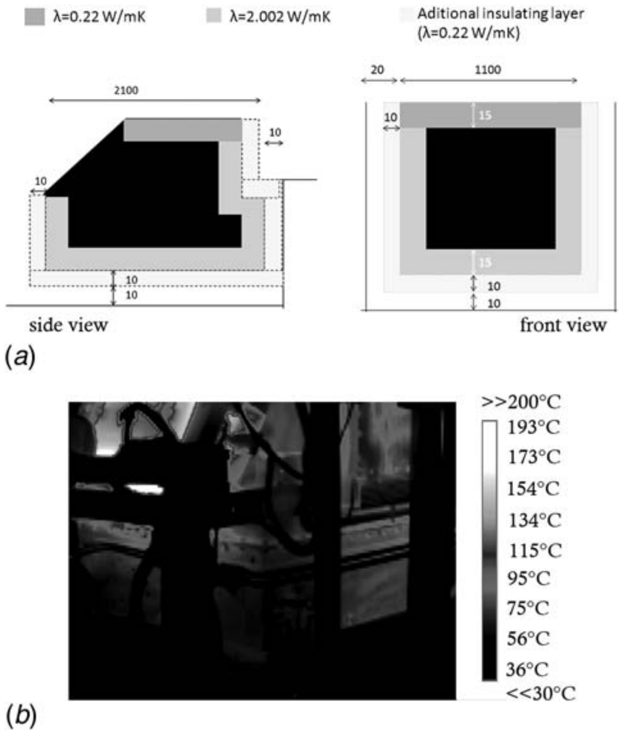

Fig. 5 The oven of the casting machine: (*a*) scheme of the oven where dimensions are in centimeters and (*b*) temperatures measured on the oven surface

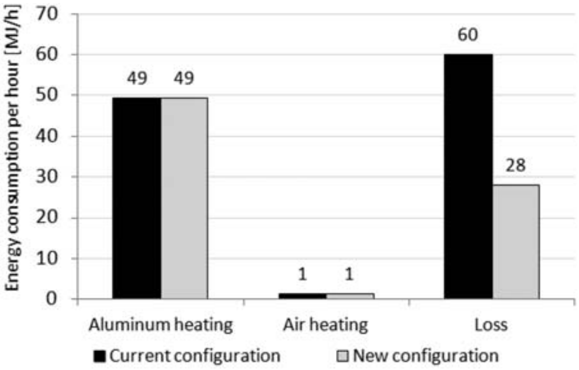

Fig. 6 Energy use distribution for the casting machine oven in the current configuration and in the new configuration with an additional insulating layer

To estimate energy η_I and exergy η_II efficiencies, the variation in temperature that occurs in the two ovens has been considered

$$\eta_\mathrm{I} = \frac{\dot{E}_\mathrm{obj}}{\dot{E}_\mathrm{fuel}} = \frac{\dot{E}^B_\mathrm{obj} + \dot{E}^C_\mathrm{obj}}{\dot{E}_\mathrm{fuel}} = \frac{\dot{m}_\mathrm{obj} c (T_2^B - T_1^B + T_2^C - T_1^C)}{\dot{m}_\mathrm{fuel}\mathrm{LHV}} = 24\% \tag{34}$$

$$\eta_\mathrm{II} = \frac{\dot{Ex}^B_\mathrm{obj} + \dot{Ex}^C_\mathrm{obj}}{\dot{Ex}_\mathrm{fuel}} = \frac{\dot{E}_\mathrm{obj} - \dot{m}_\mathrm{obj} c T_0 \left(\ln(T_2^B/T_1^B) + \ln(T_2^C/T_1^C)\right)}{\dot{m}_\mathrm{fuel}\mathrm{LHV}} = 9\% \tag{35}$$

The efficiencies are rather low and this is probably due to irreversibility in the combustion process, and the fact is that heat is transferred to air and successively to the products. A more efficient process would entail a direct heating of the discs, for example, with a laser technology.

Table 5 reports that about 68% of exergy is destroyed in the process, with a consequent great room for improvement. Since 25% of energy is lost through the utility shell, its structure has been analyzed to determine the causes of such loss. In particular, thermal resistance of the shell and thermal bridges have been investigated. Since the utility surface extends for 730 m^2, even a small specific heat flux can involve great energy loss. From Eq. (19), it appears that to limit energy flux, the shell thermal resistance must be adequate to the difference in temperature between the ambient of the factory and the ambient within the utility. From Fig. 7, it emerges that the thermal resistance of the shell is not appropriate: it is comparable to houses wall thermal resistance for which the difference in temperature is lower. In addition, as can be seen in Fig. 7(*b*), the metal pins that hold together the shell layers increase the loss given that they cross the entire shell, and they are numerous (about 20,000 pins). To assess the heat flux caused by one pin, simulations with a computational fluid dynamics-code have been performed: it has been computed that each pin entails a heat flux of 0.004 W/mK. Another weakness is represented by the rolls shown in Fig. 7(*c*). The products can move within the two ovens, thanks to revolving metallic rolls that cross the oven transversely, and their final portions protrude from the shell. There are 441 rolls, and the temperature of the extremities is 344 K.

To reduce the energy loss, it has been proposed to increase the shell thermal resistance by installing an insulating layer externally to the heat treatment oven shell. A layer of mineral wool of 0.1 m thick with thermal conductivity of 0.035 W/mK has been chosen. The installation of an additional layer determines a thermal resistance increase, the limitation of the thermal bridges due to the pins and the rolls. In this new configuration, energy η_I and exergy η_II efficiencies are 28% and 11%, respectively, and the majority of energy is used to heat the discs as shown in Fig. 8. The installation of the insulating layer would entail a fuel consumption reduction of 16 m^3/h, that is, a reduction up to 14%. Since air exits the utility at 333 K, heat waste recovery seems inappropriate.

Table 5 Allocation of energy in the heat treatment oven

	Energy per hour (MJ/h)	% of the inflow energy
Air	1745	51.0
Discs heating	810	23.7
Loss	869	25.3
Total	3424	100
	Exergy per hour (MJ/h)	% of the inflow exergy
In	3424	
Out		
Air	706	20.6
Discs heating	320	9.3
Loss	77	2.2
Total	1103	32.2
Exergy destruction	2321	67.8

5.4 Drying Oven. The drying oven is schematized in Fig. 3(*d*). The discs coming from the washing area are covered of a thin layer of water that must be removed before the application of paint. To do this, air at 423 K is blown on the products to make the water evaporate. Air is heated by the combustion of natural gas. Since the quantity of water on the discs is unknown and it varies depending on the geometric characteristics of the products, a mass of water of 24 kg/h has been hypothesized.

In this case, energy and exergy efficiencies can be defined in two ways. If only the water evaporation is considered, the efficiencies are

$$\eta_\mathrm{I} = \frac{\dot{E}_\mathrm{water}}{\dot{E}_\mathrm{fuel}} = \frac{\dot{m}_\mathrm{obj}((h_\mathrm{f} - h_1) + h_\mathrm{fg} + (h_2 - h_\mathrm{g}))}{\dot{m}_\mathrm{fuel}\mathrm{LHV}} = 7\% \tag{36}$$

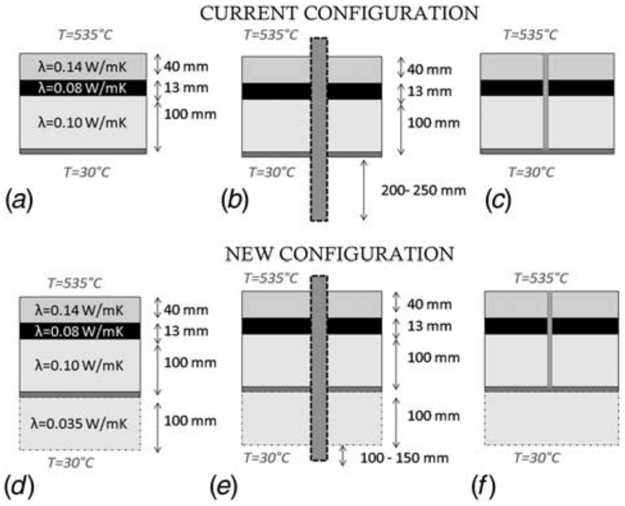

Fig. 7 Details of the heat treatment oven: (*a*), (*b*), and (*c*) layers of the heat treatment oven wall in the current configuration; (*d*), (*e*), and (*f*) new configuration with the additional insulating layer

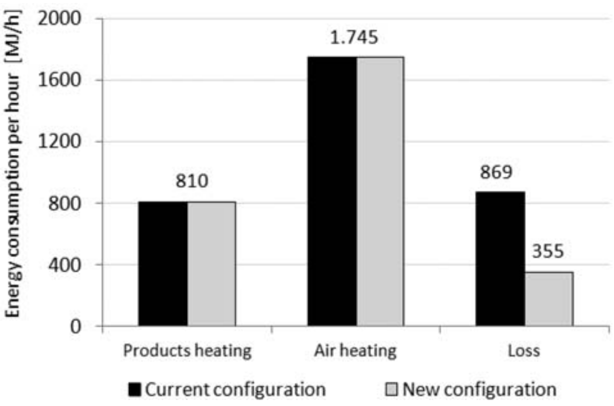

Fig. 8 Comparison between the energy use in the actual configuration and with an additional layer of insulating material for the heat treatment oven

$$\eta_{\mathrm{II}} = \frac{\dot{E}x_{\mathrm{water}}}{\dot{E}x_{\mathrm{fuel}}} = \eta_{\mathrm{I}} - \frac{\dot{m}_{\mathrm{obj}} T_0[(s_{\mathrm{f}} - s_1) + s_{\mathrm{fg}} + (s_2 - s_{\mathrm{g}})]}{\dot{m}_{\mathrm{fuel}}\mathrm{LHV}} = 1\% \quad (37)$$

where h_{fg} and s_{fg} are the enthalpy and entropy of water evaporation. If the entire process in the painting department is considered, also the heating of the discs must be included in the computing of the efficiencies, that is, by considering that the heating of the discs begins in the drying oven.

In such a case, energy and exergy efficiencies have been calculated as

$$\eta_{\mathrm{I}} = \frac{\dot{E}_{\mathrm{water}} + \dot{E}_{\mathrm{obj}}}{\dot{E}_{\mathrm{fuel}}} = \frac{\dot{E}_{\mathrm{water}} + \dot{m}_{\mathrm{obj}} c(T_2 - T_1)}{\dot{m}_{\mathrm{fuel}}\mathrm{LHV}} = 33\% \quad (38)$$

$$\eta_{,\mathrm{II}} = \frac{\dot{E}x_{\mathrm{water}} + \dot{E}x_{\mathrm{obj}}}{\dot{E}x_{\mathrm{fuel}}} = 2\% \quad (39)$$

In this second case, the energy efficiency is much higher, while exergy efficiency does not vary significantly. Then, it can be stated that the drying process involves a great destruction of exergy. This can be due to the combustion process, and heat transfer from air and then to the discs: a better technology could be researched, but this goes beyond the purpose of the study.

In Table 6, it can be seen that energy loss through the oven shell is low, and the majority of energy is exploited for increasing the temperature of air. Since air is taken from the external environment at 285 K, and the exergy content of outlet air is great, it has been proposed to increase the temperature of the inlet air by means of a heat exchanger.

It has been assumed that only 50% of the maximum heat flux is transferred to the inlet air. This hypothesis leads to an increase in temperature of the cold fluid up to 353.15 K. By preheating the inlet air, energy and exergy efficiency are 51% and 4%. In this way, from Fig. 9, it can be seen that the majority of energy is used for the water evaporation and for heating the discs. This expedient would entail a fuel saving of 21 m^3/h, that is of 30%.

5.4.1 Energy Use Comparison. For each utility in the factory, an expedient for reducing the energy demand has been proposed. Figure 10 compares the energy use in the current configuration and that estimated for the modifications proposed. The total consumption has been calculated by multiplying the consumption of the single utilities by their number. For the utilities in the painting department, the same percentage reduction of fuel consumption has been considered. The improvement of the thermal resistance of the utilities shell, and heat waste recovery can reduce the energy demand of 6049 MJ/h, that is, a reduction of the fuel consumption of about 160 m^3/h.

Table 6 Energy and exergy allocation for the drying oven in the painting department

	Energy per hour (MJ/h)	% of the inflow energy
Air	578	62.2
Discs heating	241	25.9
Water evaporation	67	7.2
Surfaces loss	43	4.7
Total	929	100.0
	Exergy per hour (MJ/h)	% of the inflow exergy
In		
Computed fuel	929	
Out		
Air	85	9.1
Discs heating	11	1.2
Water evaporation	12	1.3
Loss	3	0.3
Total	111	11.9
Exergy destruction	818	88.1

The percentage energy saving E_s has been calculated as

$$E_{\mathrm{s}} = \frac{E_{\mathrm{current}} - E_{\mathrm{newconf}}}{E_{\mathrm{current}}} \cdot 100 \quad (40)$$

where E_{current} is the total amount of energy consumed by the utilities in the current configuration, whereas E_{newconf} is the energy consumption in the proposed configuration. The energy saving in consequence to the proposed modification is equal to 15%.

5.4.2 Critical Issues in Energy- and Exergy-Based Analysis. An energy- and exergy-based analysis of a factory is a rather long and complex process.

The auditor who has to make this kind of analysis must face very complex realities. To illustrate the production process, the auditor is usually accompanied through the factory by staff that usually has a deep knowledge of only a small part of the production

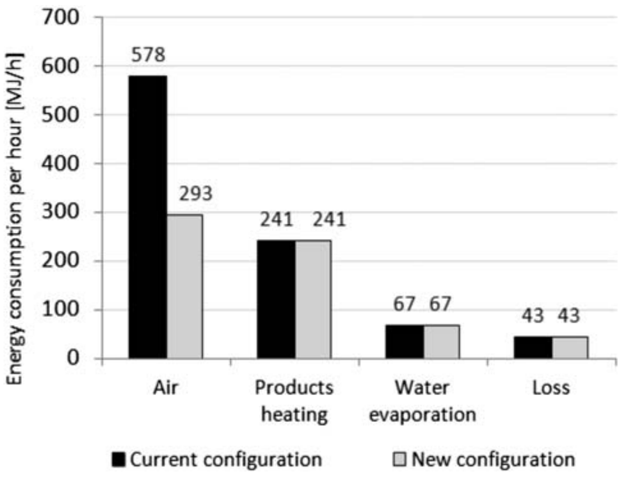

Fig. 9 Comparison between the energy use in the actual configuration and with heat recovery for the drying oven in the painting department

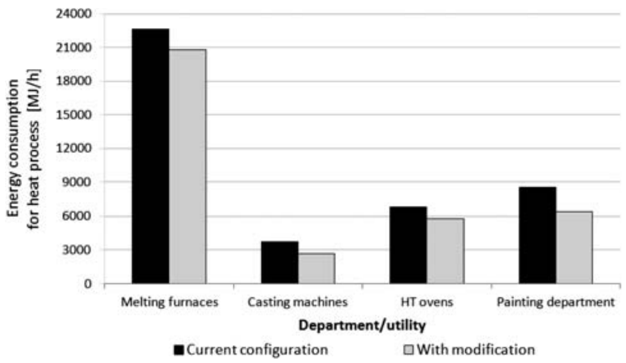

Fig. 10 Comparison between consumption of current and modified configurations

process. Then, to reconstruct the entire process, the auditor must rely on people with different preparation and process knowledge. Therefore, the company that commissions the work must choose the most qualified staff and to consent that it invests part of its time to help the auditor in understanding the production process.

To understand the entire production process, it is advisable to divide the production into levels as suggested by Ref. [8]: the factory layout should be divided into areas in which a certain type of operation is performed, such as melting process, casting process, heat treatment, and painting. Also, secondary processes not directly involved in the production must be identified. Then, each area must be analyzed to identify how processes are performed, that is, the utilities involved, and inlet and outlet quantities. Since these quantities can vary considerably from day to day, it is necessary to understand their ranges of variability. Then, it must be defined the most appropriate measuring instruments and the time intervals during which to perform the measurements. Companies wishing to do this type of analysis must be willing to buy and install the necessary measurement instruments.

Another aspect that should not be underestimated is the company willingness to communicate sensitive data. In some circumstances, certain process parameters cannot be communicated to the auditor and, consequently, hypotheses and approximations will be made. Therefore, it is necessary to know in advance what data will be available for the analysis, in order to define the level of accuracy that can be achieved. Consequently, the accuracy of the measurements can be defined: if a coarse analysis is required, the measurements will be performed on a limited time interval, otherwise longer measurements will be performed to determine parameters in different production conditions.

Only a close collaboration between auditor and staff can give rise to an accurate and fast analysis.

6 Conclusions

The study has analyzed the utilities involved in an industrial process for the production of discs made of aluminum; in particular, a melting furnace, a casting machine, a heat treatment oven, and a drying oven have been analyzed, with a focus on heat interaction. Solutions for reducing energy demand and emissions in the environment have been proposed and analyzed. It has been shown how simple expedients, such as improvement of the utilities shell thermal resistance and heat waste recovery, lead to energy saving. The percentage reduction of energy consumption between the current utilities configuration and the proposed configuration is 15%. It has also been showed that the most difficult part of the study has been the data collection. For this, all the factories interested in energy management audits should implement measurement systems to collect process data essential to energy- and exergy-based analysis. The difficulty encountered in this kind of analysis arises the need for a standardization of energy- and exergy-based analysis.

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