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# Multicriteria Analysis for Retrofitting of Natural Gas Melting and Heating Furnaces for Sustainable Manufacturing and Industry 4.0

*Different retrofitting measures can be implemented at different levels of the industrial furnace, such as refractory layers, energy recovery solutions, new burners and fuel types, and monitoring and control systems. However, there is a high level of uncertainty about the possible implications of integrating new technologies, not only in the furnace but also on the upstream and downstream processes. In this regard, there is a lack of holistic approaches to design the optimal system configurations under a multicriteria perspective, especially when innovative technologies and multi-sectorial processes are involved. The present work proposes a holistic approach to natural gas melting and heating furnaces in energy-intensive industries. A multicriteria analysis, based on criteria and subcriteria, is applied to select the most profitable retrofitting solution using the analytic hierarchy process and stakeholder expertise. The methodology is based on technical indicators, i.e., life cycle assessment, life cycle cost, and thermoeconomic analysis, for evaluating the current state of existing natural gas furnaces. Once the current state is characterized, the methodology determines the potential of efficiency improvement, environmental impact reduction, and cost-savings caused mainly by the implementation of new retrofitting solutions including new refractories, new burner concepts (co-firing), and innovative energy recovery solutions based on phase change materials. Therefore, this methodology can be considered as the first stage that guarantees technical, environmental, and economic feasibility in evaluating the effects of new technologies on the overall system performance.* [DOI: 10.1115/1.4044769]

*Keywords: alternative energy sources, energy conversion/systems, energy storage systems, energy systems analysis, fuel combustion, heat energy generation/storage/transfer*

## 1 Introduction

The aluminum industry is an energy-intensive industry (EII) contributing around 0.21% of greenhouse gas emissions generated by the industrial sector [1]. This has caused EIIs to continuously face new challenges to increase the efficiency, reliability, and competitiveness of their processes [2].

According to Gerres et al. [3], there are several equipment and strategies for potential abatement of $CO_2$ emissions, such as heat recovery, furnaces, process heat provision, and alternative feedstock. In particular, furnaces with the highest energy consumption have been the focus of multiple studies that address radical improvements in the competition, energy, environmental performance, and cost performance at the system level. For this purpose, the development of improved designs based on new

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materials, alternative feedstock, innovative equipment, and integration of permanent monitoring and control systems into new and existing furnaces is essential. This is particularly relevant in the aluminum sector because of its growing global demand despite the research on the application of new materials to develop lightweight products [4,5]. In fact, aluminum remains one of the best options for light construction compared with other materials in the coming years. Therefore, the aluminum industry is selected as a case study in this work.

In this regard, the combination of technical indicators together with environmental and economic life cycle assessments (LCAs) is a useful tool for decision-making in the aluminum industry [6–8]. These tools are aimed to identify and evaluate technical, economic, and environmental impacts attributed to all streams and processes alongside the entire value chain. In addition, they evaluate the best technological innovation for implementation.

Technological innovation is an important activity to optimize the efficient and clean use of energy and material resources by increasing process efficiency, decreasing manufacturing time, reducing energy and material wastes, and increasing productivity, among others. However, technological innovations need to be managed without partial perspectives because they can reduce their potential and limitations for sustainable growth. They need to be addressed from a holistic perspective, systemically and systematically. In particular, the LCA methodology has an important role on the basis of ISO 14040 and 14044 standards [7,8], which guarantee that the evaluation methods have been developed with substantial consistency and quality assurance. The selected indicators, e.g., global warming and ozone formation, can measure the environmental impacts of a process. These indicators help identify strategies to optimize the process from an environmental perspective. Accordingly, the LCA methodology presents interesting opportunities in the area of sustainable resource consumption [9–13].

In addition, the LCA methodology can be extended to a life cycle cost (LCC) approach, which consists of the economic evaluation of the different stages of product life cycle by the identification and quantification of four cost categories: investment, operation, maintenance, and end-of-life disposal expenses.

In addition to LCA/LCC studies, thermoeconomic analysis (TA) represents the third pillar for the development of the proposed multicriteria analysis. This is based on the combination of the second law of thermodynamics and concepts associated with an economic analysis. This analysis uses exergy accounting as a tool to evaluate the use and degradation of the energy quality and other natural resources along a system. Its final objective is to reveal potentials for process improvement in terms of types and magnitudes of destroyed exergy [14].

Using these three analyses (LCA/LCC/TA) can extract a wide range of indicators. Considering the complexity of extracting common patterns among available indicators, it is necessary to adopt a decision-making methodology that enables the whole system to achieve optimal performance according to its specific priorities. Multiple criteria decision analysis (MCDA) has been extensively used as a strategy to solve decision-making problems for various applications [15–17]. This big data management model acts as an intelligent system for identifying the optimal alternative by considering both quantitative and qualitative criteria. In particular, the analytic hierarchy process (AHP) is an MCDA strategy used for big data analytics, which will help in the transition to Industry 4.0. According to the proposed approach, AHP is applied here to combine the three pillar criteria with alternatives using a hierarchical structure as a practical tool for an optimal solution. The multicriteria analysis tool can assess the best alternative for optimizing the furnace system not only from environmental and economical perspectives but also by using an innovative methodology of sustainability optimization.

The aluminum casting sector has been selected as a case study. Using this third pillar criterion, the multicriteria analysis tool can assess the best alternative for optimizing the furnace system not only from environmental and economical perspectives but also by using an innovative methodology that will create vital knowledge for data-driven approaches and the Industry 4.0 concept. In fact, the Internet of things (IoT), cybersecurity, and integration of horizontal and vertical systems are modern technologies that will play an important role in future studies.

In summary, the current study focuses on the achievement of LCA, LCC, and TA goals, which offers guidelines to perform these methods on the aluminum sector with a special focus on natural gas melting and heating furnaces, allowing other researchers to compare them with other systems. This outcome has not been presented in other studies. This represents a unique outcome of this research since the novel multicriteria analysis, considering AHP and stakeholder expertise, is based on energy, exergy, environmental, and economic indicators considering the life cycle perspective.

## 2 Methodology

As recognized by the scientific community, Industry 4.0 represents a vision for factories of the future driven by technological advances using IoT, big data, cloud computing, simulation, augmented reality, robotics, additive manufacturing, cybersecurity, and integration of horizontal and vertical systems. The proposed methodology focuses on evaluating the implementation of disruptive technologies from previous studies, e.g., new refractories [18], new burner concepts [19], and innovative energy recovery solutions based on phase change materials (PCMs) [20] and is supported by an MCDA strategy to select an optimal solution based on multicriteria prioritization that includes both horizontal and vertical systems.

**2.1 Process Description.** In this study, the aluminum sector has been selected as a case study because of its increasing demand and rising greenhouse gas emissions. Among all stages in the processes of the aluminum sector, the more energy-intensive steps are those related to furnace systems, and hence, they are selected for this evaluation. In particular, two types of furnace systems have been selected: the first consists of an aluminum casting system fed by a melting furnace, and the second consists of an extrusion process composed by a heating furnace where aluminum is heated but not melted.

The melting unit is in charge of heating the aluminum loaded from room temperature to 730 °C (higher than its fusion temperature). The raw material introduced into the furnace mainly consists of primary aluminum mixed with traces of other elements such as silicon, iron, and magnesium. The other major raw material used is scrap, mainly composed of secondary aluminum with traces of silicon, iron, and magnesium. The furnace is fueled with natural gas and the combustion air preheated to 550 °C in an auxiliary regenerative burner to keep the aluminum alloy at 730 °C and the furnace pressure at 0–15 mbar. The main flue gas stream leaves the furnace at 950 °C (highest temperature in the furnace) from two outlets. The main exhaust gas (around 90% of the total flue gas) flows to a regenerative burner to heat the combustion air from room temperature to 550 °C and leaves the system at an outlet temperature of 145 °C. The remaining flue gas (10% of the total gas flow) is removed as hot gas drainage though a damper system (without heat recovery).

On the other hand, the second aluminum furnace system is a heating furnace that increases the billet temperature to feed the next extrusion process. This furnace also uses natural gas as a fuel and an oxidant flow, which is air previously heated in the recovery system, where its temperature is increased from room temperature to about 120–150 °C. This heating furnace can be divided into three different zones. The gas burners are at the end of the furnace, which has the highest temperature. The aluminum billet leaves this zone and the furnace at 400–460 °C, ready for extrusion. The exhaust gases generated as a consequence of natural gas combustion flow toward the second zone is called as preheating zone.

The temperature of the billet in this zone is increased to 180–200 °C. The exhaust gases then circulate through the heat recovery equipment, which acts like a heat exchanger and where part of its heat is transferred to the combustion air, as previously mentioned. Gases that are still hot are circulated again to the first zone of the furnace. The cold billet is then heated in the pre-preheating zone for the first time, from room temperature to 80–100 °C. Finally, gases are released to the environment using an exhaust fan through a chimney at 212 °C.

### 2.2 Technical Analysis.

The first stage to analyze the potential implementation of retrofitting measures consists in the comprehensive analysis of all the material and energy streams in order to evaluate relevant indicators. The most relevant indicators for the analysis of melting and heating furnaces can be described as follows:

- Net energy input (*NEI*): It is the difference between exhaust gas energy ($E_{eg}$) and fuel energy input ($E_f$), divided by the fuel energy input.

$$NEI = \frac{E_f - E_{eg}}{E_f} \tag{1}$$

The energy of each component is obtained by calculating its specific enthalpy ($h$) at the flow temperature and mass flow ($m$) using Eq. (2). For example, for exhaust gas *eg*, the equation is defined as

$$E_{eg} = h_{eg}\dot{m}_{eg} \tag{2}$$

- Melting yield (*MY*): It is ratio of the energy necessary to melt the incoming charge ($E_{Al}$) divided by the fuel energy input.

$$MY = \frac{E_{Al}}{E_f} \tag{3}$$

- Heating yield (*HY*): It is ration of the energy necessary to heat the incoming charge divided by the fuel energy input.

$$HY = \frac{E_{Al}}{E_f} \tag{4}$$

- Energy losses inside the furnace ($E_{loss}$): It is the difference between the net energy input and the total energy required to melt the incoming charge. This indicator includes all losses that can be observed in Sankey diagrams (flue gas losses, by-product losses, and losses representing radiation and convection effects).

$$E_{loss} = NEI - E_{Al} \tag{5}$$

- Recoverable energy (*RE*): It is the energy that can be recovered from exhaust gases using an energy recovery system at a minimum final temperature of the gases at the exit ($T_{min}$) of 150 °C.

$$RE = E_{eg} - m_{eg}h_{eg}(T_{min}) \tag{6}$$

### 2.3 Life Cycle Assessment and Life Cycle Costing.

LCA and LCC were performed to quantify the magnitude of environmental and economic benefits of the retrofitting measures that can be implemented at different levels of the aluminum melting and heating furnaces. The LCA methodology consists of the application of the four interactive phases well described in ISO 14040:2006 and ISO 14044:2006 standards [21,22] (goal/scope definition, inventory analysis, environmental impact evaluation, and interpretation of results). The software SIMAPRO ANALYST was used for all calculations using integrated in-house databases complemented by Ecoinvent 3.0 and ReCiPe 2016 v1.1 (Midpoint Hierarchist method); the latter was used for assignment of environmental categories using their 18 category indicators.

For the evaluation of the environmental impact of the process, the functional unit is 1 kg of raw material consisting of primary aluminum, additives, and scrap. Thus, the melting and heating systems to be studied as part of LCA are schematically presented in Figs. 1 and 2. The evaluation involves all inputs and outputs of both furnace systems. The main inputs include primary aluminum, additives, scrap (recycled), combustion air, and natural gas, while the main outputs include molten aluminum, slag, and fumes.

Regarding the second assessment included in this optimization study, the LCC methodology is based on the economic evaluation of different phases of the product life cycle. The initial capital outlay cost of an asset is normally well known and is often a key factor influencing the choice between the acquisitions of different alternatives. However, the initial capital outlay cost should not be the only factor that needs to be considered because while making the right choice for asset investment it is only a portion of the cost of an asset's life cycle.

In this sense, an LCC study aims to quantify the cost of ownership of an asset during its economic life and can be a useful tool for decision-making regarding the acquisition of different assets. Four main cost categories are assessed in this study: investment cost, operating cost, maintenance cost, and end-of-life cost.

Due to the confidentiality of the data and the fact that the data are highly dependent on the selected end user, detailed information on the primary cost is not provided in this study. Nevertheless, important results regarding the contribution of the main phases and general input categories are shown. In addition, to analyze the costs from a more standard view, TA is performed.

### 2.4 Thermoeconomic Analysis.

The first step in developing TA consists of identifying and quantifying the material and energy flows involved in this system. It is then possible to obtain the exergy balance for the same system. The exergy of material flows is formed by two components: chemical exergy, which can be found in specific databases [23], and physical exergy, whose value depends on the thermodynamic properties of the flow. Conversely, exergy of energetic flows, such as electricity and pure work, is equal to its energy. Once all exergies are calculated, exergy balances are obtained to compute the yields in terms of irreversibility and exergy of each stage. From this point, some of the most important thermoeconomic parameters, such as unit exergy cost and unit exergy consumption, are calculated. The analysis of these parameters is the main purpose of TA.

Exergy is defined as the maximum amount of work done by a system, a flow of matter, or energy as it reaches equilibrium with respect to a reference environment [24]. Irreversibility accounts for the exergy that is destroyed in a system, because unlike energy, exergy cannot be conserved. The exergy cost of a mass or energy stream is the amount of exergy required to produce it, and the unit exergy consumption is the number of exergy units required by each component from other components (or from the environment) to obtain a unit of its exergy [14].

### 2.5 Multicriteria Analysis.

Based on this methodology, all indicators are identified and prioritized into the three main domains: environmental, technical, and economic, as shown in Figs. 3–5. All previously mentioned analyses are fully integrated for a holistic approach to select the most sustainable innovation.

Figure 6 displays the structure of the visualization tool that supports the implementation of the methodology. This approach is supported by MCDA and, in particular, AHP, which helps identify the optimal solution based on multicriteria prioritization. In this study, the three main domains, i.e., environment, technical, and economic, are defined, which correspond to the first level of the hierarchy. In each domain, technical, environmental, and economic indicators have been identified, assessed, and prioritized based on stakeholder expertise.

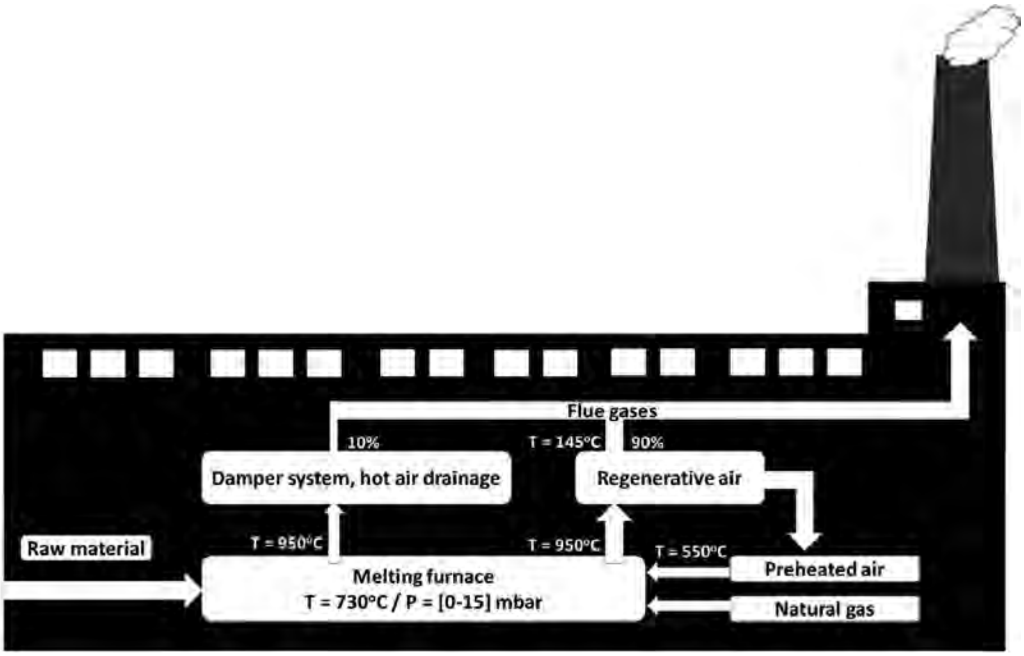

Fig. 1 System boundaries of the Al melting furnace system

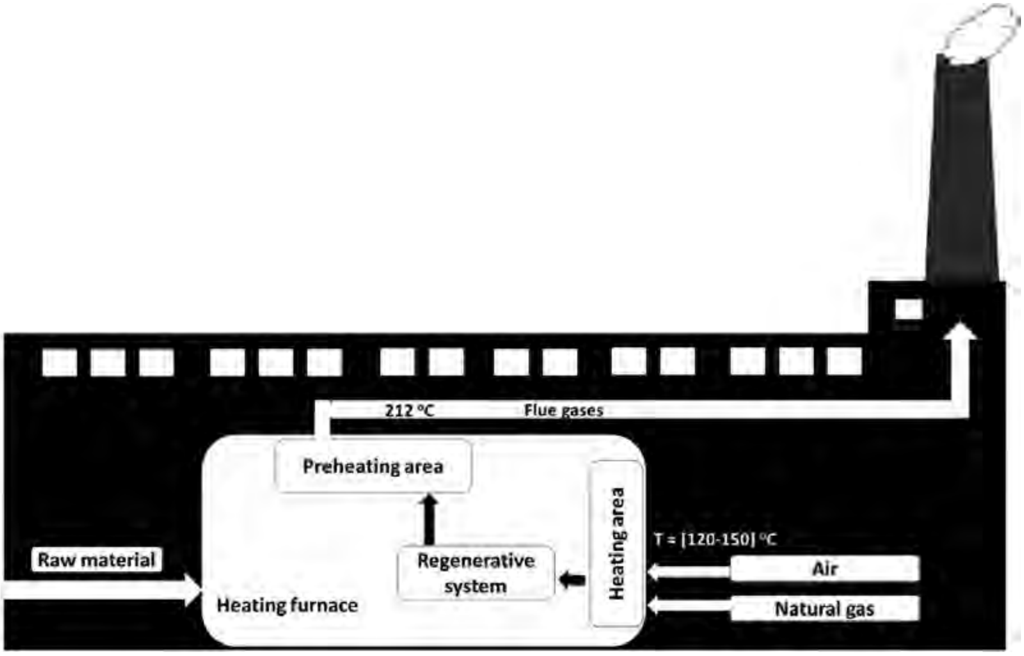

Fig. 2 System boundaries of the Al heating furnace system

The tool allows the users to visualize the complex synergies among all inputs by estimating all selected indicators for each domain extracted from AHP. According to the methodology explained in Sec. 2.2, the following technical ratios are calculated: (1) net energy input, (2) melting yield, (3) losses inside the furnace, and (4) recoverable energy from remaining exhaust gases (exhaust gases from furnace + damper − preheated air). From these values, the potential benefit from three specific strategies, exhaust gas energy recovery, improved refractories, and implementation of co-firing strategies, is calculated considering various possible indicators. Then, the program selects the retrofitting strategy with the greatest on technical indicators, followed by economic and environmental indicators.

Despite the existence of a predefined preference list obtained from selected stakeholders, the user has the option to prioritize the domains in a different order to consider the internal strategies of each production process. To conclude, an internal validation of the data is obtained by the tool using an extensive database within the software that compares the results with previously validated ranges in pilot experiences and publications.

## 3 Results and Discussion

The first step of the analysis consists of the selection of indicators used for MCDA. For this purpose, different surveys were submitted

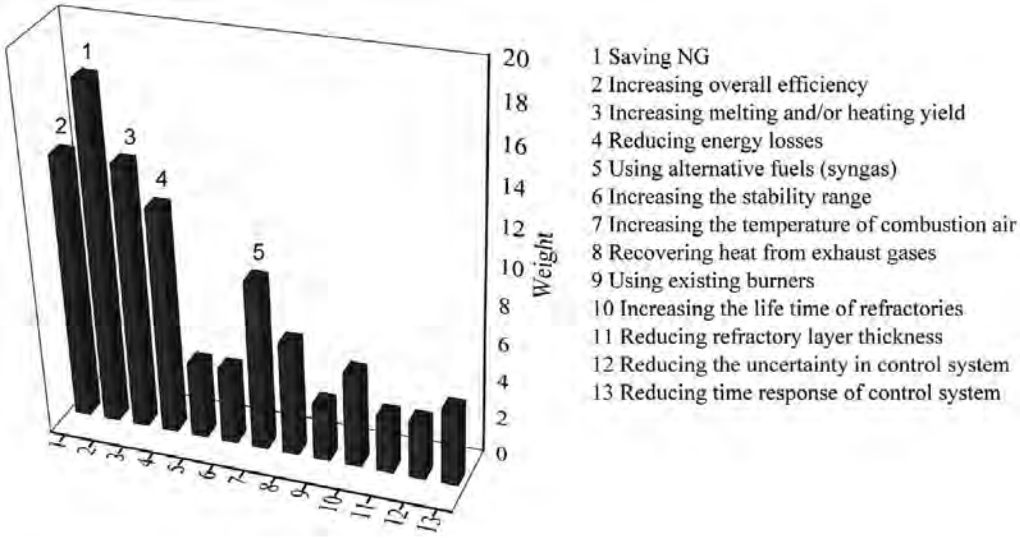

Fig. 3 Prioritization results for the indicators within the technical domain

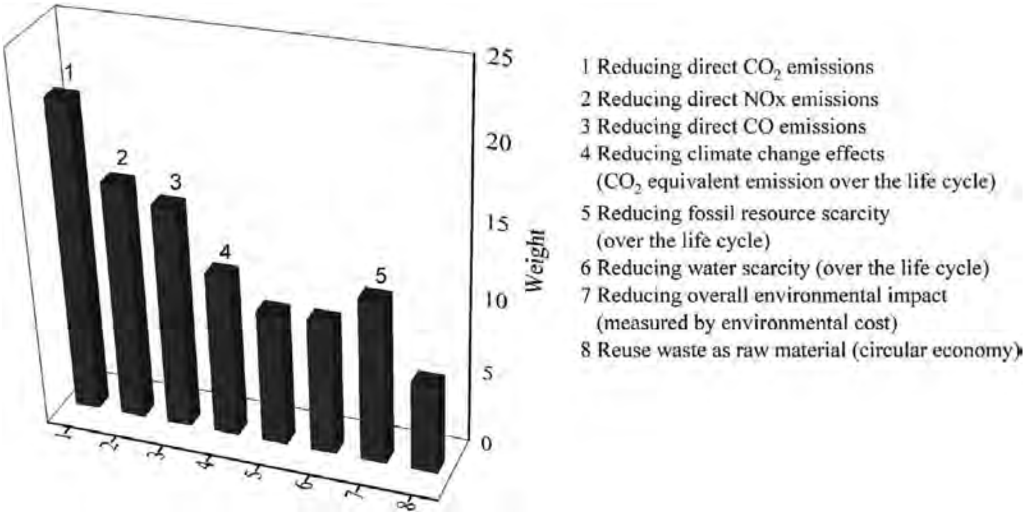

Fig. 4 Prioritization results for the indicators within the environmental domain

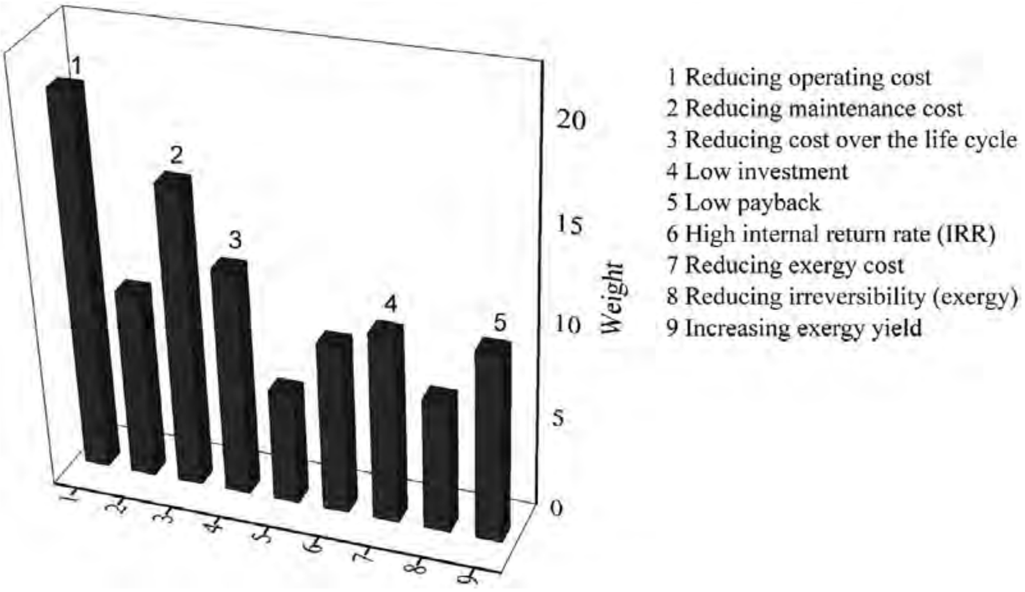

Fig. 5 Prioritization results for the indicators within the economic domain

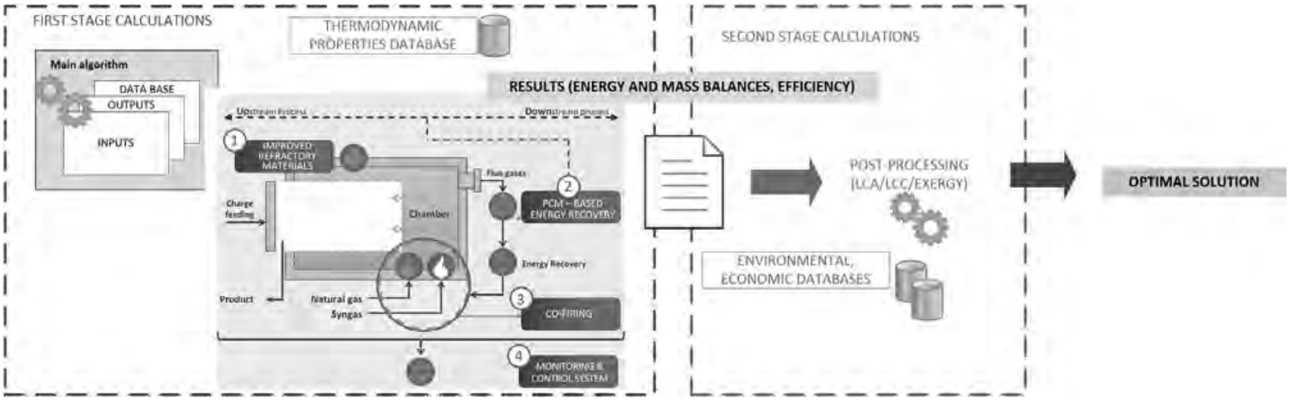

Fig. 6 Visualization tool conceptual structure

to EIIs. The first and second levels of hierarchy have been completed by selecting the most relevant criteria and deriving their priority assignment. Pairwise comparisons of the selected criteria were done by the expert panel, and the level of consistency was verified.

The results of this specific survey for the three domains, i.e., technical, environmental, and economic, are presented in Figs. 3–5.

### 3.1 Technical Indicators

*3.1.1 Melting Furnace.* First, a detailed percentage energy balance of the melting furnace is shown in Fig. 7. The reference values for computing the enthalpies in these calculations are 1 atm and 25 °C. Consequently, the input raw material (solid aluminum) and fresh air inputs do not contain energy.

Only 42% of the input energy is delivered to the aluminum. During the preheating of air, the regenerative burner can recover up to 20% of energy. In total, 7% of the energy is delivered to environment, 5% in the regenerative burner, and 2% through the damper unit. The remaining energy is converted to losses (damper and regenerative burning unit losses are 3% and 14% of energy, respectively). In the melting process inside the furnace, about 12% of energy is lost. The remaining energy losses are estimated to be about 22%. This includes uncountable losses during combustion and heat transfer (radiation and convection) from furnace openings [25]. It is worth noting that the sum of the energy furnace input is more than 100% because it considers not only the energy from the fuel but also the internal recovered energy from the regenerative burner. This fact does not affect the global energy balance.

Apart from the graphical solution, for the complete characterization of the melting furnace, the following technical indicators, explained in Sec. 2, were calculated in terms of ratios: (1) net energy input, 55%; (2) melting yield, 43%, (3) losses inside the furnace, 12%; and (4) recoverable energy from remaining exhaust gases (exhaust gases from furnace + damper − preheated air), 23%. Considering these values, it is worth mentioning that, at first sight, two different retrofitting measures can be proposed. First, due to the high percentage of recoverable energy detected from exhaust gases, the implementation of an energy recovery system seems to be promising to improve the efficiency of the entire system. Second, although the potential of improvement is lower (around 12%), the reduction in losses inside the furnace using improved refractories is another possible solution. Finally, the implementation

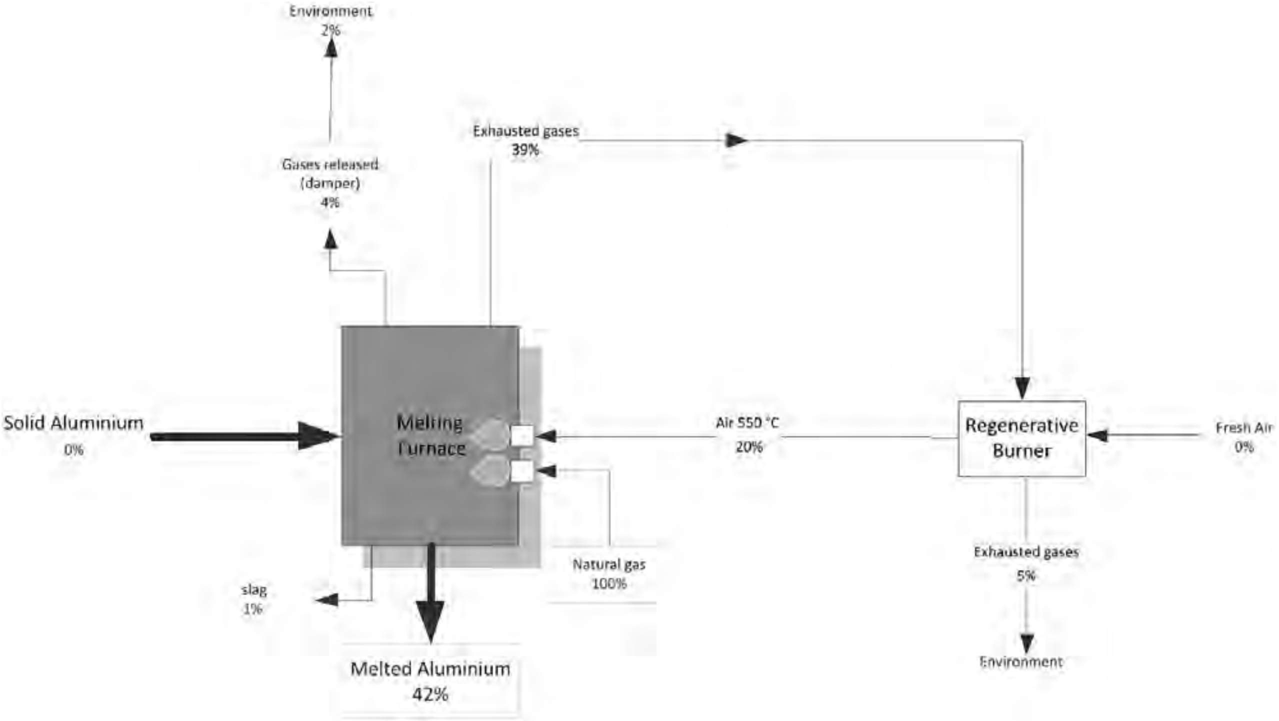

Fig. 7 Energy balance in the melting furnace

of co-firing strategies can be considered to reduce fossil fuel dependence. The most suitable solution is extracted from a multicriteria analysis using LCA/LCC/TA analysis.

*3.1.2 Heating Furnace.* The energy balance of aluminum heating process previously described is shown in Fig. 8. Since, cold aluminum billet and combustion air enter the furnace at standard reference conditions, its energy account is considered zero. Only 9% of the energy contributed by the fuel is delivered to the product. The regenerative burner unit can save up to 5% of the energy by preheating the air, and exhaust gases take off 9% of the energy from the furnace.

The regenerative burner has 2% of energy losses, which is negligible compared with the energy losses inside the furnace: 82%. These losses include losses in the combustion process, refractories, and furnace openings.

Moreover, all energy delivered to the environment through the chimney can be recovered. In this sense, it is possible to recover 9% of the energy from the exhaust gases. However, we should focus on the furnace losses, which are more than 80%. To overcome these losses, a retrofitting solution based on new refractories is required and furnace openings should be avoided.

### 3.2 Life Cycle Assessment Analysis

*3.2.1 Melting Furnace.* As previously mentioned, data collected regarding LCA of the melting stage consist of main inputs such as raw materials, primary aluminum, scrap, and additives as well as natural gas and air stream. Main outputs include molten aluminum, slag, and fumes. LCA for upstream and downstream of the furnace stage were also performed to have a global vision from environmental point of view. The reference value for all data was the functional unit (1 kg of material), which was converted appropriately using the method described above to obtain LCA results.

Therefore, based on the global evaluation in terms of percentage, the environmental performance of more than 90% in all indicators (Fig. 9(*a*)) was attributed to the raw materials and, more particularly, primary aluminum production.

It is worth noting that the contribution of raw material consumption can only be minimized by strategies that are beyond the scope of this study (e.g., increasing the use of recycled material as scrap, recycling residues, or considering less material consumption). Consequently, the evaluation of raw material has been isolated from LCA. Under this scenario, the absolute environmental performance of the entire process for the selected impact categories values are 0.16 kg $CO_2$ eq/kg Al (climate change); $8.8 \times 10^{-5}$ kg $NO_x$ eq/kg Al (ozone formation, human health); $9.6 \times 10^{-5}$ kg $NO_x$ eq/kg Al (ozone formation, terrestrial ecosystem damage), and $6.8 \times 10^{-2}$ kg oil eq/kg Al (fossil resource scarcity). The melting furnace accounts for around 18% of the global warming indicator (Fig. 9(*b*)). Despite its low impact compared to other stages, main retrofitting actions can be conducted in order to minimize the environmental impact of the implementing strategies to improve the furnace efficiency and to lower the natural gas consumption, which are expected to be evaluated as future furnace retrofitting options.

*3.2.2 Heating Furnace.* Similar to the aluminum melting process, LCA was conducted to obtain information regarding the environmental benefits of the retrofitting measures implemented at different levels of the aluminum heating furnace. As explained earlier, the case study focuses on an aluminum billet heating stage, which is considered as the most important stage in the heating furnace system. Inputs to this stage are mainly related to energy consumption in terms of natural gas and electricity, aluminum billet itself, and combustion air, while outputs are the billet heated at the required temperature and flue gases carrying surplus energy. LCA for the upstream and downstream of the heating furnace was also conducted. The main results regarding environmental impacts associated with entire aluminum heating process are depicted as percentage results in Fig. 10(*a*), which shows that processes such as heating system, extrusion, and aging have higher environmental burden. Based on the inputs and outputs for each process, environmental impacts of aging and extrusion are caused by consumption of electricity at these stages. Regarding the heating furnace, the environmental burden is associated with electricity and natural gas consumption having this latter more than 60% of impact in most indicators (78% of them). The absolute values for the selected impact categories are 0.34 kg $CO_2$ eq (climate change), $1.39 \times 10^{-2}$ kg $NO_x$ eq (ozone formation, human health), $1.40 \times 10^{-2}$ kg $NO_x$ eq (ozone formation, terrestrial ecosystem damage), and 0.13 kg oil eq (fossil resource scarcity).

Based on the heating furnace stage evaluation, it can be concluded that the effects associated with natural gas combustion, particularly natural gas consumption, are responsible for environmental impact. Considering streams involving the heating furnace, the implementation of strategies to improve furnace efficiency and minimizing natural gas consumption should be the main actions in reducing the environmental charge attributed to the furnace.

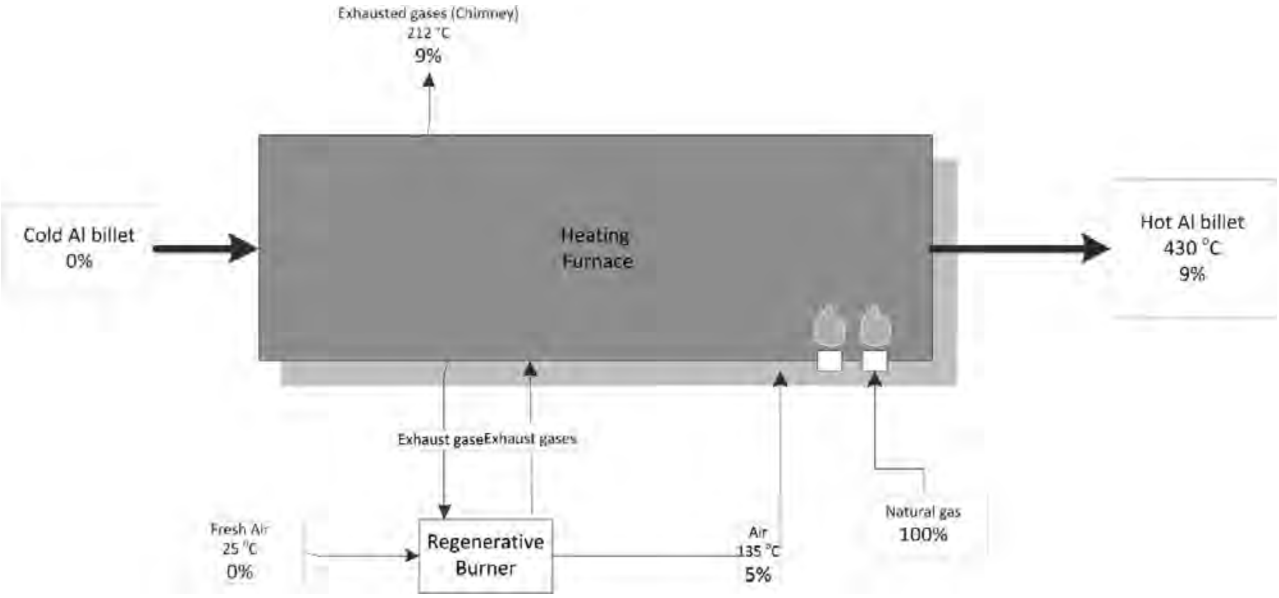

**Fig. 8 Energy balance in the heating furnace**

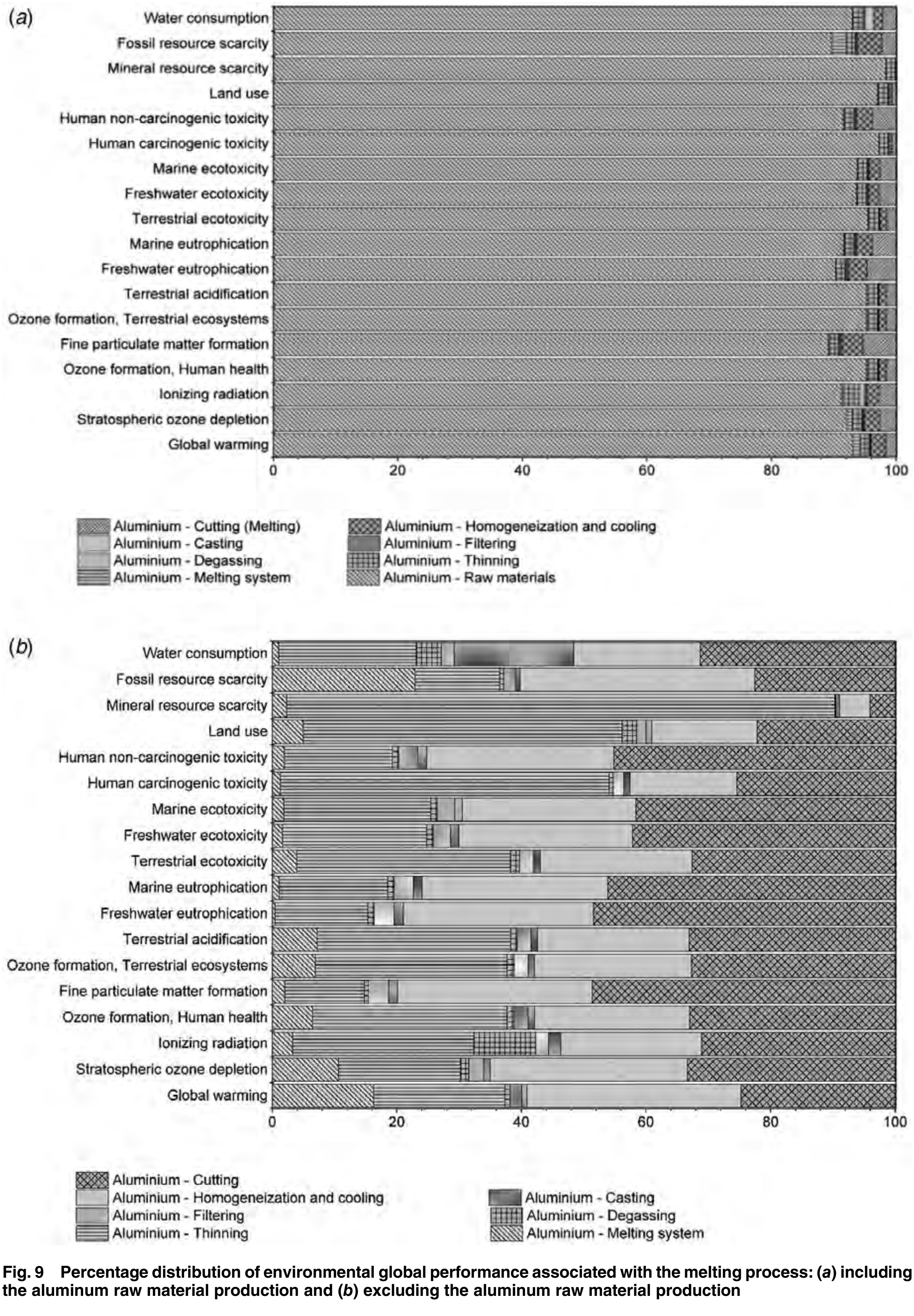

**Fig. 9 Percentage distribution of environmental global performance associated with the melting process: (*a*) including the aluminum raw material production and (*b*) excluding the aluminum raw material production**

**3.3 Life Cycle Costing Analysis.** The multicriteria tool focuses on assessing the best alternative for optimizing the operation of the furnace system. Considering this approach, the operational and maintenance costs are the most relevant aspects, and therefore, a detailed analysis was conducted for representative melting. The main results show that maintenance costs have a rather low contribution of total costs, which is mainly related to the replacement of refractories during the furnace lifetime. In terms of operational costs, the analyses involved inputs such as primary aluminum (aluminum ingots), scrap, additives, electricity,

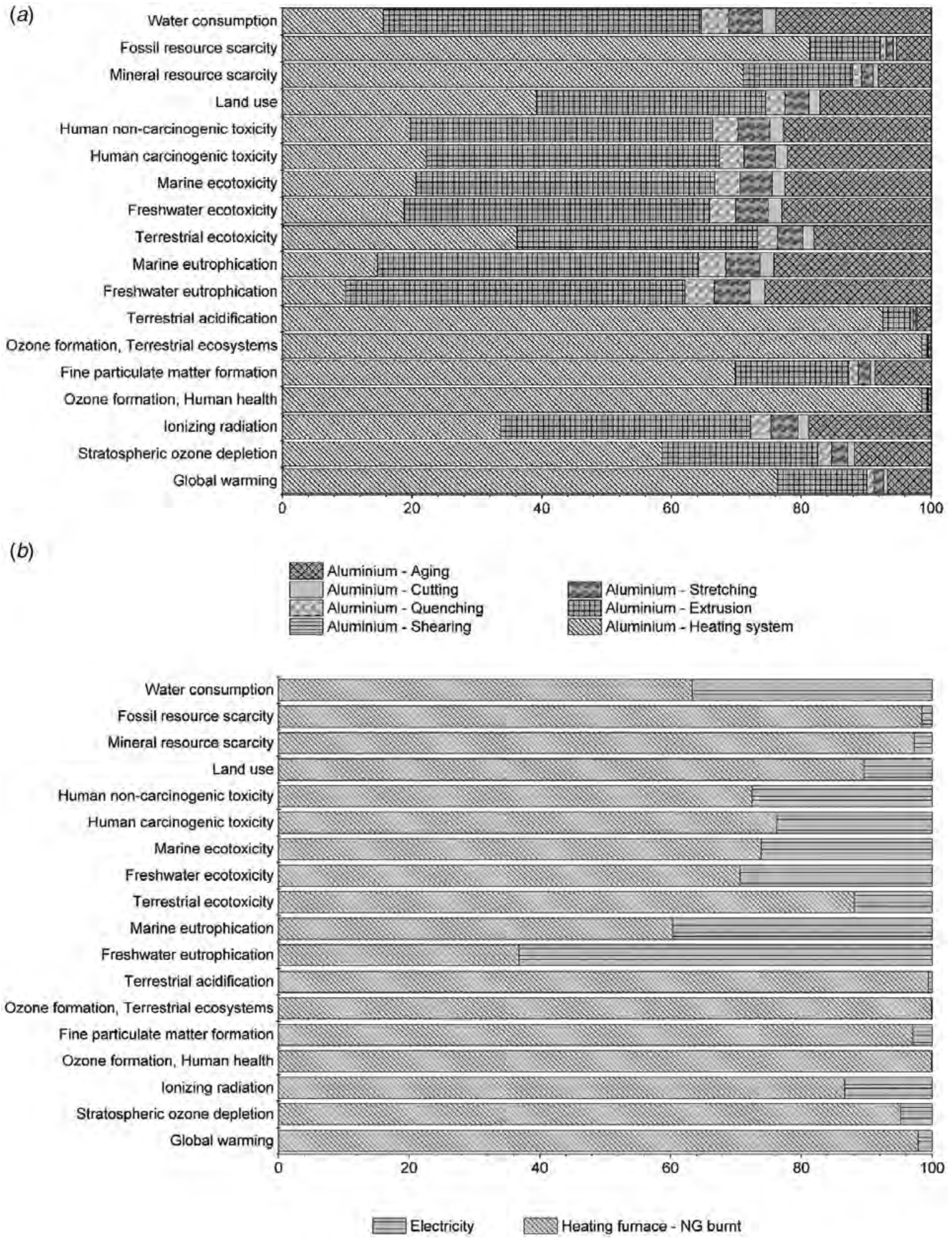

**Fig. 10 Percentage distribution of environmental global performance associated with the heating furnace: (*a*) including the whole heating/extrusion process and (*b*) heating furnace stage**

water, lubricant, personnel cost, and natural gas. The operational costs were merged into three categories: costs associated with material consumption, costs associated with natural gas consumption in the furnace, and operational costs incurred during the downstream processes. As expected, the most relevant category was the metal cost (>75%), and more specifically, the cost associated with the use of aluminum ingots as the raw material. However, as mentioned above, for replicability, direct costs are not considered for the multicriteria analysis as monetary values; instead, TA is performed.

**Table 1 Results of exergy analysis**

| Furnace | Irreversibility (kWh/h) | General exergy yield (%) | Exergy yield (only physical exergy) (%) |
|---|---|---|---|
| Melting | 1455 | 91 | 0.33 |
| Heating | 1845 | 86 | 3.10 |

**3.4 Thermoeconomic Analysis.** This analysis aims at identifying how energy is used to optimize its consumption, therefore reducing resource requirements. For this purpose, first, the exergy balances and the characterization of all flows involved in each system are obtained. Then, the parameters shown in Table 1 are calculated.

The general exergy yield, calculated as the quotient between exergy of the product and total exergy input in that stage (exergy of cold aluminum and exergy of electricity and natural gas), is 91% for the melting furnace and 86% for the heating furnace. These yields are high in both case studies due to the high chemical exergy of the entering and exiting aluminum alloy (29369.4 kJ/kg). Because both the numerator and the denominator of the exergy yield equation have high values, the result is close to one. However, completely different results are obtained if only the physical exergy of aluminum is considered in the exergy yield calculation. In the melting furnace, 1807 kWh/h of electricity and natural gas are consumed to melt 1 kg of aluminum; however, the aluminum product increases its exergy only at 6 kWh/h. This means that only 0.33% of the exergy input is incorporated in the product despite the high exergy yield. With respect to the second furnace system, the increase in exergy of the billet is 63 kWh/h, and the consumption of natural gas and preheated combustion air used in the furnace is 2025 kWh/h. Under this approach, the exergy yield is only 3.1%, which means that for 100 kWh/h of exergy introduced in the system, only 3.1 kWh/h is finally incorporated in the product. The remaining exergy is lost or destroyed.

The second part of this study included the calculation of the most relevant thermoeconomic parameters for each system. The value of unit exergy consumption for the melting furnace system is 1.07. This value is very close to one because of the high chemical exergy of aluminum. Regarding the unit exergy cost, the only product generated in this stage is melted aluminum. Considering its exergy content and exergy cost, the unit exergy cost of the furnace product is 1.069. This value is the same as the unit exergy consumption because manufacturing of by-products is not considered according to the boundary conditions previously defined. Under these premises, the sum of the fuel flows is the same as the exergy cost of the product. For the heating furnace system, its unit exergy consumption is 1.15 and unit exergy cost of heated aluminum product is 1.36. These parameters will also be calculated for the same furnace system after incorporating different retrofitting alternatives to compare the effectiveness of each proposed improvement solution.

**3.5 Multicriteria Analysis.** Increasing the overall efficiency and saving natural gas are the more relevant technical criteria. As the retrofitting solutions are directly related to the furnace system, the overall efficiency increase is proportional to the furnace efficiency, i.e., melting/heating yield. Considering the environmental aspects, reducing $CO_2$ and $NO_x$ emissions are the most relevant aspects to consider. To estimate both indicators, climate change (measured in $CO_2$eq) and ozone formation (measured in $NO_x$ eq) indicators associated with fuel use have been analyzed. Finally, as explained in Sec. 2, due to the confidentiality of the data and the level of dependence of the specific location (country, region, etc.), the economic perspective has been analyzed using TA, i.e., exergy cost indicator.

Once all individual analyses are performed, the next step consists of the holistic analysis of all extracted results. According to the technical analysis, three potential improvement solutions could be implemented within this furnace: (1) energy recovery system, (2) improved refractories, and (3) co-firing. The benefits of the three innovative solutions are estimated by considering the corresponding natural gas savings based on the impacts estimated by applying the four criteria to the three retrofitting alternatives.

By applying the methodology explained in Sec. 2, the expected impacts on selected indicators can be obtained. For example, the expected effects of three different scenarios are shown in Tables 2 and 3. The three scenarios analyzed can be described as (1) energy recovery system assuming 70% of a PCM-based energy recovery system, (2) improved refractories assuming 30% of loss reduction, and (3) co-firing for 20% of substitution ratio. Then, considering the above results and the required investment and priorities of each stakeholder, the methodology presents the optimal solution. The user has the option to prioritize the domains in a different order to consider the internal strategies of each production process.

Once the results have been obtained for each furnace and retrofitting solution, the next step includes approaching the most preferable configuration for each furnace type. For this purpose, all the indicators analyzed have been depicted in Fig. 11. Some conclusions can be extracted from the graphical analysis. Note that the lower the percentage on the figure, the more profitable is the solution to be applied.

- For the heating furnace, improvement of the furnace lining (refractories) is the solution with the most profitable,

**Table 2 Retrofitting scenarios analysis for the melting furnace system**

| Domain | | Technical | Environmental | | TA |
|---|---|---|---|---|---|
| Innovation | MY (%) | Volume NG saved/mass Al ($Nm^3$/kg) | $CO_2$ emissions ($gCO_2$ eq/kg Al saved) | $NO_x$ emissions $gNO_x$ eq/kg Al saved | Exergy cost reduction (Wh/kg Al) |
| Energy recovery | 65 | 0.024 | 54 | 0.063 | 48 |
| Refractories | 57 | 0.018 | 40 | 0.047 | 6 |
| Co-firing | – | 0.014 | 48 | 0.037 | – |

**Table 3 Retrofitting scenarios analysis for the heating furnace system**

| Domain | | Technical | Environmental | | TA |
|---|---|---|---|---|---|
| Innovation | MY (%) | Volume NG saved/mass Al ($Nm^3$/kg) | $CO_2$ emissions ($gCO_2$ eq/kg Al saved) | $NO_x$ emissions $gNO_x$ eq/kg Al saved | Exergy cost reduction (Wh/kg Al) |
| Energy recovery | 10 | 0.001 | 26 | 2.706 | 78 |
| Refractories | 37 | 0.098 | 198 | 20.040 | 365 |
| Co-firing | – | 0.039 | 78 | 8.119 | – |

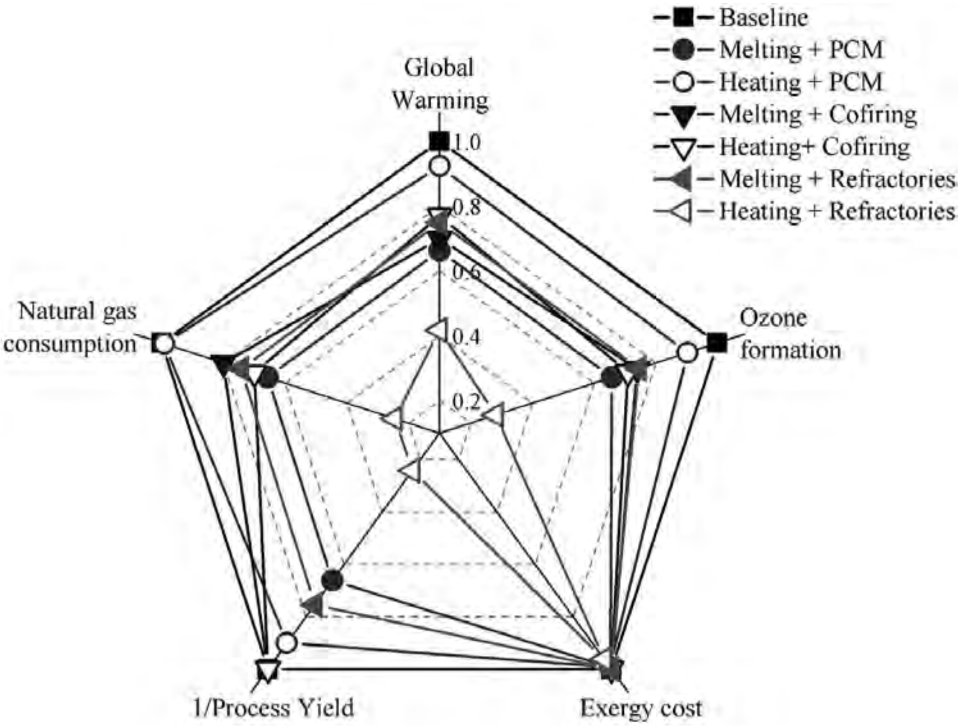

Fig. 11 Multicriteria analysis diagram

whereas integration of a PCM-based energy recovery system is the least profitable.

- For the melting system, the most convenient solution is the implementation of a PCM-based energy system partially due to the high energy content of exhaust gases [26]. Improvement of refractories would be the second option for the selected indicators.
- Co-firing implementation displays a similar effect on all indicators analyzed independently of the furnace type.
- The reduction in the exergy cost of the product caused by the incorporation of retrofitting solutions strongly depends on the natural gas saving. However, when analyzing the relative impact of the implementation of each solution, all the innovations present a small impact on the exergy cost reduction because the high chemical exergy of the processed products remains unchanged.

It is noteworthy that the obtained results are validated using an extensive database within the software, which compares the results with previously validated ranges in pilot experiences and publications.

## 4 Conclusions

For Industry 4.0, industrial data should be processed using advanced mathematical techniques, including MCDA for integrating process and/or system and selecting high impact technologies to be applied. To improve the efficiency of industrial furnaces, different retrofitting measures can be implemented, such as refractory layers, energy recovery solutions, and new burner (co-firing) strategies. However, due to the high level of competition in the market, decision-makers need a holistic perspective to foresee the effects of new technologies on the overall system performance and generate new advances to facilitate the implementation of Industry 4.0. To solve this challenge, a novel approach based on technical indicators, LCA, LCC, and TA, has been presented. Then, a multicriteria analysis, based on criteria and subcriteria, has been applied to select the most profitable retrofitting solution using AHP and stakeholder expertise.

Using this approach, two case studies on the aluminum sector have been thoroughly analyzed. The first case study is the aluminum melting furnace, where more than 40% of the energy is utilized for melting. Also, 23% of the energy is saved by recovering exhaust gases that are being delivered to the environment. The second case study demonstrated that the aluminum heating furnace has an enormous potential in saving energy directly in the chimney and through the furnace walls and openings. Different options have been evaluated resulting in different scenarios that can be applied individually or together. Once the multicriteria analysis was provided by the tool, a prioritization strategy was applied to identify the most convenient option. For this purpose, additional analysis such as the evaluation of potential investment and the internal return rate is required. Consequently, this methodology can be considered as the first stage that guarantees technical, environmental, and economic feasibility, which considers and integrates horizontal and vertical value chain analyses as a pillar of Industry 4.0 previous to apply more complex engineering calculations.

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## Nomenclature

$f$ = fuel
$h$ = enthalpy, kJ/kg
$m$ = mass flow, kg/s
$E$ = energy, kWh/h
$T_{min}$ = minimum temperature of exhaust gases
$eg$ = exhaust gases

*loss* = losses
*Al* = aluminum
*HY* = heating yield, %
*MY* = melting yield, %
*NEI* = net energy input, kWh/h

## References

[1] Gautam, M., Pandey, B., and Agrawal, M., 2018, "Chapter 8—Carbon Footprint of Aluminum Production: Emissions and Mitigation," *Environmental Carbon Footprints*, S. S. Muthu, ed., Butterworth-Heinemann, London, pp. 197–228.

[2] Galitsky, C., Worrell, E., Masanet, E., and Crijns-Graus, W., 2008, "Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry." An ENERGY STAR Guide for Energy and Plant Managers.

[3] Gerres, T., Chaves Ávila, J. P., Llamas, P. L., and San Román, T. G., 2019, "A Review of Cross-Sector Decarbonisation Potentials in the European Energy Intensive Industry," J. Cleaner Prod., **210**, pp. 585–601.

[4] Ferreira, V., Egizabal, P., Popov, V., García de Cortázar, M., Irazustabarrena, A., López-Sabirón, A. M., and Ferreira, G., 2019, "Lightweight Automotive Components Based on Nanodiamond-Reinforced Aluminium Alloy: A Technical and Environmental Evaluation," Diamond Relat. Mater., **92**, pp. 174–186.

[5] Tisza, M., and Czinege, I., 2018, "Comparative Study of the Application of Steels and Aluminium in Lightweight Production of Automotive Parts," Int. J. Lightweight Mater. Manuf., **1**(4), pp. 229–238.

[6] Mardani, A., Zavadskas, E. K., Khalifah, Z., Zakuan, N., Jusoh, A., Nor, K. M., and Khoshnoudi, M., 2017, "A Review of Multi-Criteria Decision-Making Applications to Solve Energy Management Problems: Two Decades From 1995 to 2015," Renewable Sustainable Energy Rev., **71**, pp. 216–256.

[7] Cinelli, M., Coles, S. R., and Kirwan, K., 2014, "Analysis of the Potentials of Multi Criteria Decision Analysis Methods to Conduct Sustainability Assessment," Ecol. Indic., **46**, pp. 138–148.

[8] Franco, A., and Diaz Vazquez, A. R., 2006, "A Thermodynamic Based Approach for the Multicriteria Assessment of Energy Conversion Systems," ASME J. Energy Resour. Technol., **128**(4), pp. 346–351.

[9] Royo, P., Ferreira, V. J., López-Sabirón, A. M., García-Armingol, T., and Ferreira, G., 2018, "Retrofitting Strategies for Improving the Energy and Environmental Efficiency in Industrial Furnaces: A Case Study in the Aluminium Sector," Renewable Sustainable Energy Rev., **82**, pp. 1813–1822.

[10] Ibáñez-Forés, V., Bovea, M. D., and Pérez-Belis, V., 2014, "A Holistic Review of Applied Methodologies for Assessing and Selecting the Optimal Technological Alternative From a Sustainability Perspective," J. Cleaner Prod., **70**, pp. 259–281.

[11] López-Sabirón, A. M., Aranda-Usón, A., Mainar-Toledo, M. D., Ferreira, V. J., and Ferreira, G., 2014, "Environmental Profile of Latent Energy Storage Materials Applied to Industrial Systems," Sci. Total Environ., **473–474**, pp. 565–575.

[12] Aranda-Usón, A., Ferreira Ferreira, G., López-Sabirón, A., Llera-Sastresa, E., and de Guinoa, A. S., 2012, "Characterisation and Environmental Analysis of Sewage Sludge as Secondary Fuel for Cement Manufacturing," 15th International Conference on Process Integration, Modelling, Prague, Czech Republic, August, Vol. 29.

[13] Caravaca, A., Ferreira, V. J., de Lucas-Consuegra, A., Figueiredo, J. L., Faria, J. L., Valverde, J. L., and Dorado, F., 2013, "Simultaneous Production of H2 and C2 Hydrocarbons by Using a Novel Configuration Solid-Electrolyte + Fixed Bed Reactor," Int. J. Hydrogen Energy, **38**(8), pp. 3111–3122.

[14] Torres, C., Valero, A., and Valero, A., 2013, "Exergoecology as a Tool for Ecological Modelling: The Case of the US Food Production Chain," Ecol. Modell., **255**, pp. 21–28.

[15] Diaz-Balteiro, L., González-Pachón, J., and Romero, C., 2017, "Measuring Systems Sustainability With Multi-Criteria Methods: A Critical Review," Eur. J. Oper. Res., **258**(2), pp. 607–616.

[16] Strantzali, E., and Aravossis, K., 2016, "Decision Making in Renewable Energy Investments: A Review," Renewable Sustainable Energy Rev., **55**, pp. 885–898.

[17] Motamedi, P., Bargozin, H., and Pourafshary, P., 2018, "Management of Implementation of Nanotechnology in Upstream Oil Industry: An Analytic Hierarchy Process Analysis," ASME J. Energy Resour. Technol., **140**(5), p. 052908.

[18] Ferreira, G., López-Sabirón, A. M., Aranda, J., Mainar-Toledo, M. D., and Aranda-Usón, A., 2015, "Environmental Analysis for Identifying Challenges to Recover Used Reinforced Refractories in Industrial Furnaces," J. Cleaner Prod., **88**, pp. 242–253.

[19] Ferreira, G., Barreras, F., Lozano, A., Antonio Garcia, J., and Lincheta, E., 2009, "Effect of Inner Two-Phase Flow on the Performance of an Industrial Twin-Fluid Nozzle With an Internal Mixing Chamber," Atomization Spray, **19**(9), 873–884.

[20] Ferreira, V. J., López-Sabirón, A. M., Royo, P., Aranda-Usón, A., and Ferreira, G., 2015, "Integration of Environmental Indicators in the Optimization of Industrial Energy Management Using Phase Change Materials," Energy Convers. Manage., **104**, pp. 67–77.

[21] International Standardization Organization, 2006, "ISO 14040 Environmental Management—Life Cycle Assessment—Principles and Framework."

[22] International Standardization Organization, 2006, "ISO 14044:2006, Environmental Management—Life Cycle Assessment—Requirements and Guidelines."

[23] Exergoecology, 2013, "The Exergoecology Portal," http://www.exergoecology.com, Accessed October 12, 2018.

[24] Rosen, M. A., and Dincer, I., 2001, "Exergy as the Confluence of Energy, Environment and Sustainable Development," Int. J. Exergy, **1**(1), pp. 3–13.

[25] Mullinger, P., and Jenkins, B., 2013, "Chapter 6—Combustion and Heat Transfer Modelling," *Industrial and Process Furnaces*, 2nd ed., P. Mullinger, and B. Jenkins, eds., Butterworth-Heinemann, Oxford, pp. 209–243.

[26] Royo, P., Acevedo, L., Ferreira, V. J., García-Armingol, T., López-Sabirón, A. M., and Ferreira, G., 2019, "High-Temperature PCM-Based Thermal Energy Storage for Industrial Furnaces Installed in Energy-Intensive Industries," Energy, **173**, pp. 1030–1040.