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LIFE CYCLE ANALYSIS OF STEEL MADE IN THE ELECTRIC ARC FURNACE WITH ECCENTRIC BOTTOM TAPPING

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The importance of steel life cycle study is presented through steel elaboration technology that allows the use of scrap metal by recycling them; the paper presents an analysis of data from industrial practice, and the potential impact caused on the environment. The purpose of the work is to identify and present the environmental impact generated by the steelmaking process in the electric arc furnace with eccentric bottom tapping (EBT).

The article also presents the identification of opportunities and risks associated with three approaches for the steel development process based on scrap metal in the electric arc furnace.

Keywords: electric arc furnace, steel life cycle, steel making process.

1. Introduction

Steel, one of the most present materials in daily life, with a wide area of use, from construction and infrastructure to general-purpose goods, is 100% recyclable material. According to WorldSteel, in the first month of 2023, a world production of crude steel of 145.3 million tons (Mt) was reported, which is likely to continue to grow amid global events (the war in Ukraine, the earthquakes in Turkey and Syria) and due to the fact that this material cannot be replaced by other materials.

In industrial practice, steel is produced in principle on two process paths: blast furnace (BF) - basic oxygen furnace (BOF), and electric arc furnace (EAF) route, (load consisting of metal waste, direct reduced iron (DRI), respectively, different by-products obtained from iron ores or small and powdered waste with high iron content) [1-3].

Fig. 1 shows the steel production flows related to the two routes mentioned above. The representation of technological flows was made after studying the references [1-3], identifying the processes (sintering, coking) and the installations

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related to them, with the help of which the raw materials (iron ore, coal) that are processed, part of the furnace load is processed.

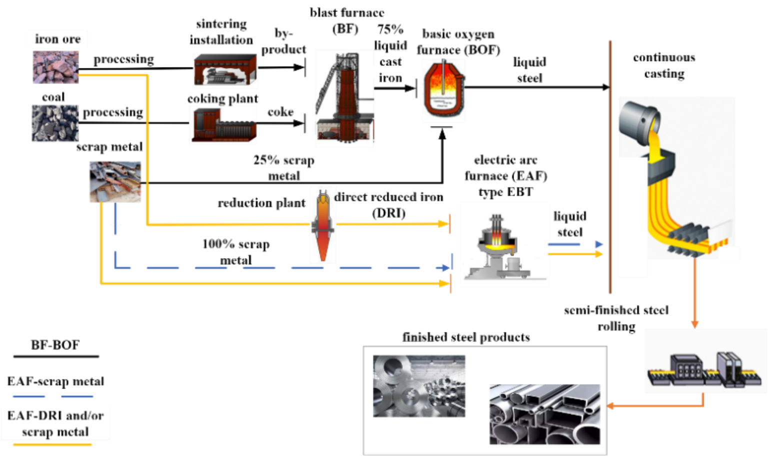


Fig. 1. Steel manufacturing flows, adaptation according to [1-3]

The technological process for obtaining steel on the BF-BOF route consists of processing iron ore and coke to load them into the blast furnace. A certain amount of cast iron elaborated in the blast furnace is loaded into the oxygen converter to make steel. The liquid steel developed in the converter is poured with the help of a continuous casting plant. Steel blanks (bars, blooms, billets, etc.) are processed by various processes, such as lamination to obtain finished steel products (pipes, sheet metal, etc.), which are used in various industries.

In the EAF-scrap metal route, waste is the only raw material used in steelmaking. This is only possible in the electric arc furnace (classic or EBT-Eccentric Bottom Tapping type), which allows a load consisting of 100% metal waste. Once the steel is elaborated, it is discharged into the casting pot, continuously poured, cooled, and processed, to obtain the finished products. The way in which the technological process is carried out on the EAF-DRI and/or by-products route is the same as in the case of the EAF-scrap metal route.

Annually, approximately 70% of the steel produced worldwide is manufactured on the BF-BOF route (in 2020 the share was 73%) [4], of the type that on the EAF route only about 30% of the world's quantity of steel is produced [2].

Steel waste has significant economic value, which is why the demand for recycled materials in markets is well established; Steel is recycled in a closed loop so that the properties of the primary product produced from primary resources (iron ore, limestone, coal) and the by-product made from waste are equivalent [1,5].

The provenance of waste that can be introduced into steelmaking processes is clearly defined in ISO 14021:2016 and they are [1]: internal waste: steel scrap from steelmaking processes in the converter or in the electric arc furnace; preconsumer waste: materials diverted to the waste stream during a manufacturing process; post-consumer waste (waste from the population, end-of-life vehicles, scrap metal, etc.).

Worldwide, the global need for steel waste for the steel industry exceeds the availability of waste (due to the long service life of steel products) [1,4], hence the smaller quantity of steel produced in the electric arc furnace.

The use of waste as secondary raw materials in the steelmaking process slows the rate of depletion of raw material resources, saves energy, and generates a decrease in the level of CO_2 emissions generated in the air, according to WorldSteel, around 650Mt of steel waste is recycled each year, avoiding the release of 945Mt of CO_2 [6].

The recovery rate for steel waste is currently estimated to vary in the range of 50-90%, while only almost 30% of all new steel products are made from recycled steel waste (since considerable material losses are recorded in steelmaking streams); however, given the sustainable life cycle of steel (around 75% of steel products ever manufactured are still used today) [2] and the steel-consuming industries, waste recovery and recycling rates remain below 100% [6].

The main advantages of steelmaking processes over those of other advanced materials are the recycling property, conservation of natural resources, extensive reuse of by-products, and relatively low energy consumption [7,8].

Each product goes through a series of phases during its lifetime; in the case of steel, they are as follows: Phase 1: extraction of raw materials, auxiliary materials/ their processing; Phase 2: elaboration of steel; Phase 3: manufacture of steel products necessary for various industries; Phase 4: use of steel products in various industries; Phase 5: use, reuse, and reconditioning of products built on the basis of steel; Phase 6: collection, processing, and recycling of scrap metal; At the end of the process, the recycled material is transformed into a new product, and the cycle begins again.

The steel life cycle shown in Fig. 2, and the implicit identification of phases 1, 2, 3, 4, 5 and 6, was carried out following the reference study [2,9]. The authors considered that phase 6 (collection, processing, and recycling of scrap metal) is of the greatest importance, the recycling activity of collected waste can replace the need to extract and process raw materials.

It is important to note that the life cycle of any product, in this case steel, is usually divided into the following steps [10]: *cradle to entry gate* (extraction and refinement of raw materials); *entry gate to exit gate* (manufacture of the product); *exit gate-to-grave* (use, disposal of products, and recycling).

In a sustainable society, the circular economy aims to minimize the use of raw materials by encouraging practices to reduce the quantities of raw materials consumed, by promoting reuse, refurbishment, and recycling activities. To ensure the achievement of a circular economy, it is recommended to take into account the life cycle analysis approach to measure environmental benefits [11].

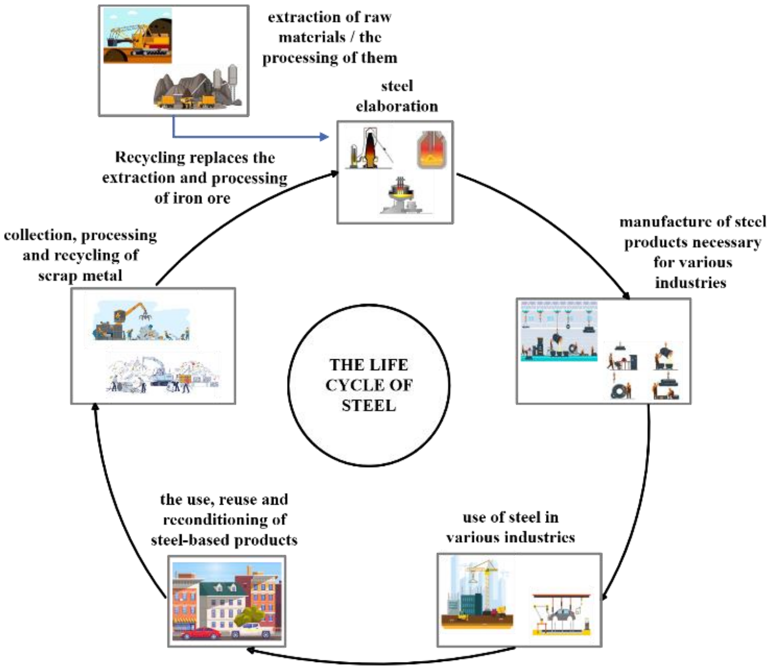


Fig. 2. Representation of the steel life cycle, adaptation according to [2,9]

Other variables that occur in the steel life cycle and are not detailed in Fig. 2 are related to the recycling of by-products (residues generated in the steelmaking process are recirculated in different production streams) [5,8].

Life cycle assessment (LCA) is an environmental management tool that is used to determine the impact generated over the lifetime of a system/process/product [1,2,12,13].

ISO standards regulating the application of life cycle analysis methodology, which include available requirements and guidelines, on methodological options, and the establishment of transparency and reporting rules, are ISO 14040: 2006 and ISO 14044: 2006 [1,2].

The purpose of this paper is to present the impact generated by the steel development process in the electric arc furnace, on the environment by applying the life cycle methodology, also aiming at identifying the opportunities and risks associated with the metal scrap steelmaking process through life cycle approaches.

2. Methodologies

In this paper, the authors aim to apply the life cycle analysis methodology in the process of developing steel manufactured on the basis of metal scrap in the electric arc furnace. The environmental balance sheets related to the steel development process in a steel company and the presentation of the potential impact caused are presented, respectively, exemplifying the classic life cycle approaches for the steel production case.

According to the ISO 14044:2006 standard, the LCA methodology is structured on four main components that have been customized and adapted to the steelmaking process, these are [1,14]: *Defining the purpose of the study*, *the scope*, *and identification of the limits of the steel development process in the electric arc furnace; Inventory analysis of scrap steelmaking in the electric arc furnace*; *Impact assessment of waste-based steelmaking in the electric arc furnace*; *Interpretation of results.*

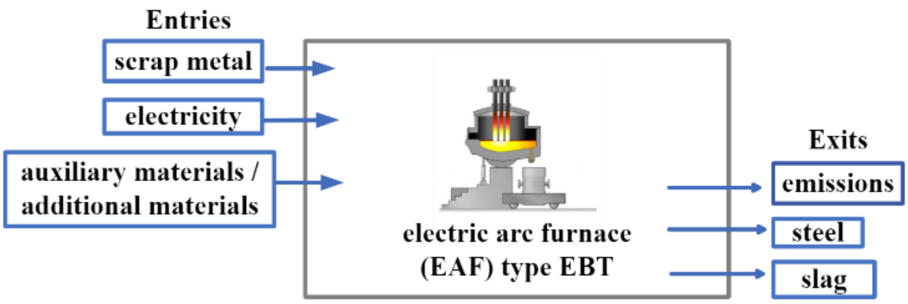
In the framework of this paper, the application of the LCA methodology is aimed at the steelmaking process, following the four previously mentioned components.

2.1. Application of LCA methodology to the waste-based steelmaking process in the electric arc furnace

- ***Defining the purpose of the study, the scope, and identification of the limits of the steel development process in the electric arc furnace***

The functional unit is represented by the variation of the quantities of secondary raw materials (scrap metal) that are used in the elaboration of steel in the electric arc furnace, within a steel company.

The limits of the steelmaking process in the electric arc furnace, where secondary raw materials differ (scrap metal, scrap metal, and by-products) are shown in Fig. 3. In Fig. 3a, metal scrap, electrical input, and steel, slag, output [4]. We mention that these inputs and outputs are specific to all electric arc furnaces, in the present case an EBT type electric arc furnace and, in the case of reference, a classic electric arc furnace. In Fig. 3b, for the direct reduction plant, hydrogen, methane gas, electricity inputs, and iron output sponge were identified by the reference study [4].



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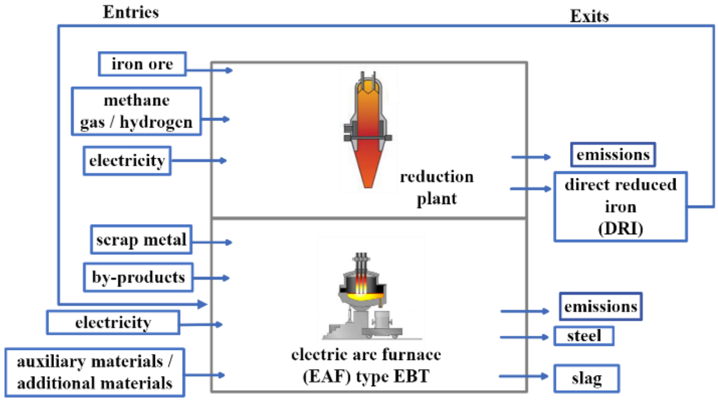

b

Fig. 3. The limits of the steelmaking process in the EAF, adaptation according to [4]
a - Limits of the waste-based steelmaking process in the electric arc furnace
b - Limits of the crude steel production system by a direct reduction plant and an electric arc furnace

- ***Inventory analysis of scrap steelmaking in the electric arc furnace***

To perform the steel life cycle inventory, internal documents from a steel company were consulted and analyzed, identifying the amounts of input and output related to the flow of waste-based steel production in the electric arc furnace. A collection of data specified in the technical development documents (bill of lading) was carried out to determine the liquid steel removal rate.

The main characteristics of the electric arc furnace with eccentric steel discharge through the hearth, within which the process of elaboration of steel based on scrap metal is carried out, are the following [15,16]: Capacity: 100t; Power of the transformer: 75MVA; Diameter of the bowl: 6400mm; Weight of discharge charge (batch-quantity of liquid metal in a single processing operation): 100t; Charge duration: 75 minutes.

Technical data on the composition of the metal load during steelmaking in the electric arc furnace and the removal of liquid steel during processing are presented in Table 1. The method of calculating the removal of steel is determined according to the relation (1).

$$Removing\ steel\ = \frac{elaborate\ steel}{metal\ load} \times 100, [\%] \tag{1}$$

Three working variants were analyzed: the composition of the metal load from scrap metal waste in a proportion of 100% (different assortments and degrees of conditioning); the use, at a rate of 12-24% of crusts in addition to scrap metal waste; complex metal load, consisting of 19-21% of cast iron waste, 7-9% by-products obtained from the briquetting of small and powdered waste and the rest of scrap metal. In all the cases analyzed, the quality of the metal load clearly influenced the amount of steel developed. For these reasons, steel producers should turn to the use of well-prepared and controlled loads.

Table 1

Removal of liquid steel in an electric arc furnace working

Composition of the load	Remove steel [%]
ferrous waste (scrap)	78,5 –95,51
ferrous waste (scrap metal) and crusts	85,32–94,01
ferrous waste (scrap metal), cast iron waste, and by-products	76,42–95,15

Tables 2 and 3 show the inputs and outputs related to the steelmaking process, (preset for electric arc furnaces), and concrete values, from industrial practice.

Table 2

Input from the steelmaking process in the electric arc furnace [15]

Input type	Preset entries		Concrete inputs	
	Entry	Values	Entry	Values
Raw materials	Scrap	1080–1130kg/t elaborate steel	Scrap	1119kg/t of elaborate steel
	Lime	30–80kg/t elaborate steel	Lime	49kg/t elaborate steel
	Graphite electrodes	1,5–4,5kg/t elaborate steel	Graphite electrodes	4kg/t elaborate steel
	–	–	Ferroalloys	14 kg/t elaborate steel
	–	–	Slag	≈ 100–150kg/t elaborate steel
Energy	Electricity	638,89–750kwh/t elaborate steel	Electricity	699kwh/t elaborate steel
	Oxygen	24–47m^3/t elaborate steel	Technological oxygen	21m^3/t elaborate steel
	–	–	Methane gas	15m^3/t elaborate steel
Water	–	Included in the cooling circuit	Industrial water (recirculated water, WATER DEMIN., Softened water)	40m^3/t elaborate steel

Table 3

Output streams of the steelmaking process in the electric arc furnace [15]

Output type	Preset outputs		Concrete outputs	
	Exit	Values	Exit	Values
Products	Liquid steel	1t	Liquid steel	1t
By-products	Furnace slag	10–3 kg/t liquid steel	Furnace slag	125kg/t liquid steel
	–	–	Steel waste	12kg/t liquid steel
	Dust	10–20kg/t	Dust	≈ 10–20kg/t steel
Emissions	Powders	1–780g/t liquid steel	Particulate matter	270g/t liquid steel
	SO_2	24–130g/t liquid steel	SO_x	0,150 g/t liquid steel
	CO	740–3900g/t liquid steel	–	–
	–	–	CO_2	79g/t liquid steel

- ***Impact assessment of waste-based steelmaking in the electric arc furnace***

During this phase of the LCA methodology, the objective was to detail the effects of air, water, and soil pollution caused by the steel development process in the electric arc furnace.

Air pollution

In steel, the rules according to which the monitoring and management of emissions to the air are carried out are not only referred to as Best Available Techniques (BAT). To generate air emissions, a steel company is required to comply with several BATs, of which we mention the following [16]: BAT 87 – preventing mercury emissions as much as possible; BAT 88 – gas capture generated in the electric arc furnace using the combined technique of direct capture of waste gases in the fourth hole of the vault and hood system.

Within the steel elaboration phases (loading, melting, oxidation, steel exhaust), the gas emissions depollution equipment used is the bag dedusting plants, which have an efficiency of 99,9% [16]. Dust resulting from the treatment of primary and secondary gases in the arc furnace dust installation arc furnace must be transported and stored in enclosed spaces to avoid exposure of dust to weathering and, therefore, avoid contamination of soil and air [16]. The activity of steel elaboration in the electric arc furnace generates certain specific pollutants (CO, CO_2, SO_x, NO_x), according to the legislation, the generator is obliged to report them, especially if the exceedances of the limit values are recorded.

The development of steel in the EBT electric arc furnace is a modern technological process, although technology is highly efficient, the pollutants' emissions generated exceed similar emissions obtained in the EU countries [15].

Water pollution

The water used in the steel development process in the electric arc furnace is polluted with pollutants such as suspensions, oils, petroleum products, and heavy metals. For its treatment in industrial practice, hydrocarbon separator-type plants are used [16]. The main quality indicators monitored for the determination of water emissions are pH, temperature, matter in suspension, Fe content, Zn content, Ni content, Cr content, which are monitored, according to internal documents of a steel company, quarterly and monthly, respectively [16]. Modern steel plants operate with closed cooling systems attached to the electric arc furnace; water is recirculated in the system, purified, and discharged into rivers [15].

Following the study of the internal documents of a steel company in the Hunedoara County area, we would like to specify that the company's practices regarding wastewater resulting from the activity of steel elaboration in the electric arc furnace fall within the norms related to the discharge of wastewater into natural emissaries. The practice of cooling water recycling activities in the system reduces the amount of water pollution generated in the water.

Soil pollution

Potential sources of soil pollution generated by the steel elaboration process in the electric arc furnace are determined: by dispersion of powders that have a significant heavy metal content (Pb, Zn, Cd, Cu, Ni), long storage/storage of by-products and/or raw materials directly on the ground, accidental leakage/discharge of petroleum products from means of transport [15-17].

Exceeding the alert thresholds established in the law in force triggers additional monitoring from the competent authorities. Monitoring of soil pollutants is recommended to be performed annually, the optimal depth of sampling, according to the internal documents studied, is 5cm.

According to studies and analyses carried out by operators / specialized personnel on soil pollution phenomena, caused by steel elaboration processes, it appears that near the process site and in the surrounding areas, the concentrations of pollutants in the soil were within the limits of the alert threshold. On the other hand, the soil inside the steelmaking department, on the other hand, is significantly polluted with heavy metals (lead, cadmium, zinc, etc.).

- ***Interpretation of results***

The steel elaboration process in the electric arc furnace generates an impact on air, water, and soil, but by using appropriate and high performance technologies (flue gas treatment plants, wastewater treatment plants, and industrial water recirculation, adopting measures to prevent heavy metal deposits in the soil, using and arranging concrete platforms for inputs and outputs), the impact is continuously monitored, taking care not to exceed the limit values set by law.

2.2. Classic life-cycle approaches for the steel production case

The life cycle approaches applicable to steel that have been identified and will be studied in this work are [2]:

- Approach cradle-to-cradle — provides for the analysis of the life cycle situation in which the material is recycled, in the same type of material, without losing its properties, (in the case of steel).
- Approach cradle-to-gate — provides for the analysis of a product from the extraction phase of the raw materials to the point where the product leaves the factory.
- Approach gate-to-gate — provides for the analysis of a product from the reception of raw materials to the completion of the production process.

The importance of the three types of approaches, is given by the possibility of identifying both opportunities (to reduce the consumption of raw materials, to make energy consumption more efficient, etc.) and the risks involved in obtaining a product or applying a technology.

Fig. 4 was produced following the study [1,18] that allowed the authors to familiarize themselves with the concepts of the three approaches, identifying the boundaries of these approaches.

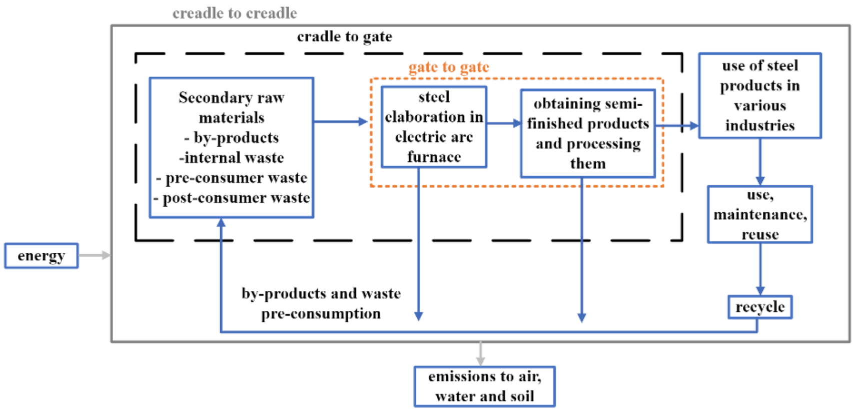

Fig. 4. Representation of lifecycle approaches applied to the steelmaking process and system boundaries, adaptation according to [1,18]

In Table 4, an analysis of steel life cycle approaches is presented, including the identification of opportunities and risks associated with the steelmaking process in the electric arc furnace using by-products as secondary raw materials.

Table 4

Identifying opportunities and risks associated with the scrap metal-based steelmaking process

Life-cycle approaches	Opportunity	Associated risks
Cradle to cradle ↓ Cradle to gate ↓ Gate to gate	- By using 100% of the waste in the ferrous load, the use of primary resources is eliminated; - Possibility of using by-products from small and powdery waste with high iron content; - Identification of ferrous waste generators that may be suppliers of secondary raw materials; - Implementation of BAT-type solutions which, in addition to economic and technological advantages, generate a decrease in environmental impact; - Use of own waste, with controlled chemical composition; - Win & win partnerships with steel processors to return the generated ferrous waste.	- Supply of ever-decreasing quantities of ferrous waste (scrap metal); - Supply of scrap metal with uncertain chemical composition; - Supply of qualitatively inferior ferrous waste (with earthy materials, rust, light or heavy waste that must be conditioned before use); - The use of unsuitable ferrous waste (ferrous fraction slag), which leads to a decrease in the removal of liquid steel when draughting; - Generation of ferrous products with lower quality levels; - Possibility of delays in the supply flow; - Improper mechanical and technological characteristics.

An analysis to identify the associated opportunities and risks related to each approach was not performed because during the steel development process in the electric arc furnace the approaches follow/derive from each other; as can be seen in Fig. 4, the identified opportunities and associated risks are generally valid for the three types of waste-based steel life cycle approaches in the electric arc furnace.

3. Conclusions

The environmental impact caused by the steel development process in the electric arc furnace is estimated to be significant, but, by monitoring and controlling emissions on the main environmental factors (air, water, soil), the pollution level does not exceed the limits allowed and established by the norms. The steelmaking process in the electric arc furnace contributes to the reduction of environmental impacts, using waste as sources of secondary raw materials, energy consumption is minimizing, and significantly reducing significantly reducing significantly reducing greenhouse gas emissions are significantly reduced.

The application of the LCA methodology to the waste-based steel development process in the electric arc furnace resulted in an exhaustive presentation of the results, as well as the identification of a set of opportunities and risks associated with steelmaking technology in the electric arc furnace, for types of life cycle approaches. The opportunities identified include the following:

- The possibility of using 100% of the waste in the ferrous load allows for the replacement/elimination of the use of primary resources (iron ore) and the application of circular and green economy concepts;
- The use of its own waste, with controlled chemical composition in the elaboration process;
- Development of win-win partnerships with steel blank processors to return ferrous waste, for use in the composition of the electric arc furnace load.

As risks, the following may be mentioned:

- Supply of ever decreasing amounts of ferrous waste (scrap metal) — due to the increasing life cycle time of ferrous products;
- Generation of ferrous products with lower quality levels due to the poor quality of the waste used in the load, materialised by inadequate mechanical and technological characteristics;
- The appearance of delays in the scrap metal supply flow of scrap metal.

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