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Combining organizational and product life cycle perspective to explore the environmental benefits of steel slag recovery practices

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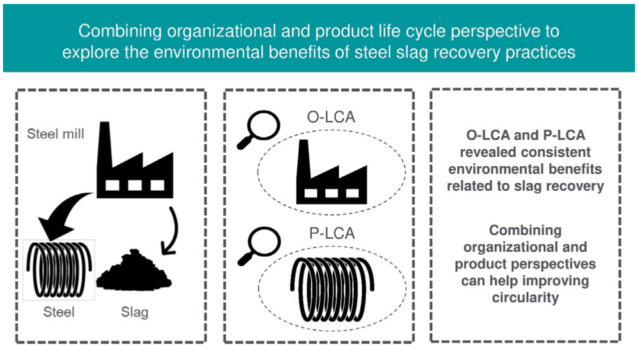
HIGHLIGHTS

- The environmental improvements of a plant generating steel slag are assessed.
- Life Cycle Assessment is applied from an organizational and product perspective.
- Allocation and system boundaries are the main methodological aspects revealed.
- Lower impacts are obtained if the steel slag is recovered and not landfilled.
- Combining organizational and product perspectives can help improving circularity.

GRAPHICAL ABSTRACT



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ABSTRACT

Sustainability in steel production is considered a global challenge which needs to be faced with coordinated actions. The aim of this study is to assess the environmental improvements of a steel mill in a circular economy perspective, through the Organizational Life Cycle Assessment (O-LCA) and the Product Life Cycle Assessment (P-LCA) methodologies. This study explores to what extent the improvements and the efforts to recover the steel slag can be detected using an organization perspective and making a comparison with the more traditional product perspective.

The results obtained show that the case in which the steel slag is recovered has lower impacts than the case in which it is landfilled through both O-LCA and P-LCA applications and that the percentage variations are similar for 8 categories out of 10 demonstrating that for our case study, O-LCA and P-LCA can detect the efforts to recover slag similarly. Two categories, namely ADP-minerals&metals and EP-freshwater, are affected by the greater amount of metal and mineral raw materials needed if the slag is not treated and by the steel slag landfill disposal more significantly. What the results tell us is that the variations obtained for this study in the P-LCA application are greater than those obtained in O-LCA application, due to two methodological aspects, namely the application of allocation procedures and the choice of the system boundaries. Finally, it emerges that O-LCA methodology can detect environmental improvements of circularity practices, but the reduction of the impacts is less clear than P-LCA application. What is transferable is that O-LCA and P-LCA methodologies are not interchangeable to quantify the environmental benefits and address the efforts to improve a process in terms of circularity.

1. Introduction

Sustainability in steel production is a key focus of research due to its increasing concerns that affect global warming (Farjana et al., 2019); it is a

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global challenge which needs to be faced with coordinated actions aimed at improving the environmental conditions (Nidheesh and Kumar, 2019).

In 2000, the crude steel production was around 850 million tons in the world; and in 2020 it reached 1878 million tons. Nowadays, the major steel producing countries are China, India and Japan, with 1064.8, 100.3 and 83.2 million tons of crude steel produced in 2020, respectively. Italy ranks among the 15 major steel producing countries with 20.4 million tons of crude steel produced, out of which 15.3 million tons produced via Basic Oxygen Furnace (BOF) technology and 84.7 through Electric Arc Furnace (EAF) and it ranks among the 10 major indirect exporters countries in the world of steel finished equivalent (World Steel Association, 2021).

As the steel industry is the basis of many countries' economies, it has received much attention and the synergy among the environment, resources and the economy has become a research hotspot (Liu et al., 2021). Among the various environmental impact assessment tools that are widely used to quantify the environmental performance, Life Cycle Assessment (LCA) is recognized as an effective tool by practitioners and researchers (Farjana et al., 2019) and by policy makers (Stewart et al., 2018), also for exploring the circular transition (Sigüenza et al., 2021).

In the last ten years, several LCA studies have been conducted in the steel sector, for instance, Burchart-Korol (2013) performed an LCA of steel production in Poland. Renzulli et al. (2016) developed an LCA of the steel production occurring in the largest integrated EU steel mill, located in the city of Taranto in southern Italy. Liu et al. (2020) and Liu et al. (2021) conducted large-scale research from environmental and economic perspectives, and they applied the LCA methodology to analyse the major iron-mining, steel-making, and steel-trading countries, including Italy.

Steel slag is the main source of solid waste in the steel industry (Díaz-Piloneta et al., 2021) and recent research indicates that circularity practices have the potential to provide significant environmental benefits (Broadbent, 2016; Conejo et al., 2020; Minunno et al., 2020). Due to the rapid increase in the generation of steel slag, there is an urgent need to manage the disposal or utilization processes. Nowadays, approximately 77 % of steel slag in Europe, for instance, is used as a substitutional material to produce cement or utilized as construction materials (Li et al., 2022). Incorporation of steel slag not only rectifies the disposal problems associated with slag, but also reduces the environmental impact of the products where it is used (Ferreira et al., 2016; Nidheesh and Kumar, 2019).

Moving from the LCA studies applied to steel products to the LCA studies focusing on products which incorporate steel slag, several applications can be found, such as Sayagh et al. (2010), Chen et al. (2011), Mattila et al. (2014) and Xiao et al. (2014). Mladenovič et al. (2015) carried out an LCA to compare the environmental impacts of the construction of asphalt wearing courses with the use of siliceous aggregates and the use of alternative steel slag aggregates. The main advantage of the alternative scenario was that a reduction could be achieved in the consumption of natural aggregate and in the quantity of slag deposited on landfill sites. Anastasiou et al. (2015) developed a comparative LCA of six different concrete road pavements and analyzed three types of binders; their results showed that concrete road pavements with high volume of alternative materials could reduce the emissions. Crossin (2015) explored the use of ground granulated blast furnace slag as a cement substitute and Feiz et al. (2015) showed that cement products that contained a large proportion of ground granulated blast furnace slag from the iron and steel industry, had lower emissions. Several concrete mixes having similar basic properties were evaluated by Turk et al. (2015) and compared with a corresponding conventional concrete mix. Their results indicated that the use of the alternative and recycled materials was beneficial in the concrete production industry. Other studies focused on the comparison of different products that incorporate steel slag, such as Ferreira et al. (2016), Anastasiou et al. (2017), Di Maria et al. (2018), Evangelista et al. (2018), Liapis et al. (2018) and Di Maria et al. (2020). Four other studies were developed about the use of steel slag in the asphalt pavements (Bonoli et al., 2020; Lizasoain-Arteaga et al., 2020; Díaz-Piloneta et al., 2021; Wang et al., 2021) and two studies about the use of sleet slag in concrete (Alzard et al., 2021 and Václavík et al., 2020).

Different recommendations have been conceptualized by Li et al. (2022) regarding the quantification of the environmental impacts of steel slag, and they regard the selection of the functional unit, system boundaries, data collection, system expansion and allocation, impact categories and sensitivity analyses.

Even if the LCA methodology was originally developed for products, it is also possible to employ it at organizational level. Organizational LCA (O-LCA) analyses the whole organization including not only the facilities of the organization but also upstream and downstream activities and provides organizations with environmental understanding at the level at which most of the decisions are made—the level of the organization—thus supporting them effectively to improve their environmental performance (Martínez-Blanco et al., 2015a; Martínez-Blanco et al., 2015b). The requirements and guidelines for O-LCA are described in ISO (International Organization for Standardization) (2014). According to Pelton et al. (2016), O-LCA can be considered as another manifestation of a portfolio approach, requiring organizations to consider their entire portfolio of suppliers and distributors across all operating units. Martínez-Blanco et al. (2018) and Forin et al. (2019) highlight that O-LCA is still a rather young proposal but at the same time it is becoming more broadly accepted as a scientifically mature and practical method. Some of the first case applications were published in 2016 (i.e. Jungbluth et al., 2016; Resta et al., 2016) and more recently, Alejandrino et al. (2022) proposed a methodology capable of evaluating and prioritizing circularity practices built on the O-LCA application.

Our research embraces the recommendations conceptualized by Li et al. (2022) and explores the challenges regarding the system boundaries definition and the burdens allocation, going beyond the product perspective and developing an organizational perspective. Thus, our research questions (RQs) are:

- RQ1: To what extent the environmental benefits of the steel slag recovery practices can be detected at organizational level.
- RQ2: To what extent the environmental benefits of the steel slag recovery practices are reflected on the product level.

Our research evaluates the environmental improvements of a plant generating and recovering the steel slag by using the Organizational Life Cycle Assessment methodology (O-LCA) and moving the attention from the product incorporating the steel slag, already investigated in the scientific literature, to the plant generating the steel slag. Thus, the novelty of this research is twofold:

- The application of O-LCA has been explored by some authors in the last years, but it is still an under-explored topic. There are no applications of O-LCA in the steel manufacturing sector, nor in the utilization of the steel slag, confirming the need of further applications.
- This study detects the benefits of the steel slag recovery from a completely new perspective, never investigated in the scientific literature so far, namely from the perspective of the plant generating the steel slag and evaluating if the benefits are consistent with the product perspective.

In doing this, our research:

- Contributes to the debate on the rapid increase of steel slag generation globally and to improve the disposal or utilization processes' management.
- Contributes to further explore the steel slag utilization, which unlike other well investigated solid waste materials, is still little explored as sustained by Li et al. (2022) in their literature review.
- Contributes to the development of strategies for policymakers shifting from the "one size fits all" approach to differentiated approaches, as sustained by Gao et al. (2019) and encourages the implementation of steel slag recovery practices improving the sustainability of the global steel industry according to the need highlighted by Cui et al. (2020).

This study explores a case study to highlight the practical implications of the environmental management of steel slag from the perspective of the organization generating it. This explorative research improves the knowledge about the application and the environmental effectiveness of circularity practices not only from a product perspective but from an organizational perspective.

Our research reveals that it is advisable to detect the circularity practices' efforts not only related to the recycled products but also for the plant generating them. The advantages and the efforts to improve circularity are also discussed.

2. Methodology

The analysis of the extent to which the circularity practices can be detected at organizational level and how these practices have an impact on the product level is conducted for a case study. The research was developed through four steps.

Firstly, the subject of the research is chosen. The selected subject of the research must allow to assess the environmental impacts of a plant adopting a circular economy practice by using the O-LCA and the product LCA (P-LCA) methodologies in combination. It has to contribute to learn new lessons by extending the previous knowledge and being a “revealing case” as discussed by VanWynsberghe and Khan (2007). A steel mill with a specific circular economy practice is selected for this purpose and is described in Section 2.1. A steel mill is a production process in which circular economy perspective plays a key role (Evangelista et al., 2018), considering indeed the reuse and the recycling of the generated steel slags.

Secondly, to answer RQ1, the O-LCA methodology according to ISO 14072 (ISO (International Organization for Standardization), 2014) is applied to the selected case study. The O-LCA application is presented in Section 2.2. Thirdly, to answer RQ2, the P-LCA methodology according to ISO 14040 (ISO (International Organization for Standardization), 2020a) and ISO 14044 (ISO (International Organization for Standardization), 2020b) is applied. The product LCA application is presented in Section 2.3.

2.1. Subject of the research

The subject of the research is a steel mill including an Electric Arc Furnace (EAF), two hot-rolling mills, three cold-rolling mills and the slag processing area.

Raw materials from all over the world are transported to the plant, where they are stored and then fed into the production cycle. The ferrous scrap, together with pig iron and cast iron, slag-forming additives and coal, is loaded into the EAF where, by means of electrical energy and the energy generated by the oxidation reactions resulting from the insufflation of oxygen, the melting of the materials takes place. Two streams are generated from this point, the liquid steel mass and the electric arc furnace carbon steel slag (EAF-C). The liquid mass is then transferred to the ladles and the necessary ferroalloys are added. Once chemical and thermal homogeneity has been achieved through the addition of energy, the liquid steel is poured to form billets. The billets are then processed at hot rolling mills, producing wire rods and rebars, which can be sold directly or processed in cold-rolling mills. In these mills cold rolling and winding operations are carried out. The obtained stretched wire is destined for sale or to produce electro-welded mesh. From a circular economy perspective, the EAF-C is physically processed to make it usable in the construction industry. The EAF-C is cooled by spraying water and stored for curing. It is then moved to the processing plant, where the deferrization, crushing and sieving processes take place. This EAF-C, which has a size of up to 14 mm, can be applied for the construction of bituminous road surfaces and concrete conglomerates. Thanks to this practice of circular economy, it is possible to valorize a material that otherwise, after the curing process, would be landfilled.

2.2. Organizational Life Cycle Assessment (O-LCA)

The phases to perform an O-LCA study according to the ISO (International Organization for Standardization) (2014) are four: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of results.

2.2.1. Goal and scope definition

During this phase, the reporting organization is identified. The selected reporting organization is defined as the whole organization which consists of a single facility, as described in Section 2.1. The divisions included are steel plant, rolling mills, slag recovery plant, laboratory for quality and technological tests, chemical and geotechnical laboratory, logistics, administration, research and development. The organization holds the full operational control of the steel plant, thus only one site is included in the system boundaries and the operational control is selected as consolidation approach. The operation control approach facilitates the collection of data and the implementation of potential improvements identified through O-LCA, as highlighted in UNEP (2015). The reference period is one year, namely 2020.

The reporting flow is the whole product portfolio, namely wire rods, rebars, stretched wire, electro-welded mesh, and EAF-C thus, allowing a complete and accurate picture of the product portfolio.

The system boundaries were defined according to the ‘cradle to gate’ approach. This choice is justified by the fact that the organization has no influence on the use stage and the end-of-life stages of its products and applied in other studies. The system boundaries include the extraction and processing of input materials, the EAF process, the ladle furnace and the continuous casting, the hot rolling process, the stretching, and the cold rolling. The steel slag process is also included. Fig. 1 shows these activities and the related consumption of materials and resources, waste generated, the transport of materials from production site to the steel mill, the transport of waste and the internal transport with forklifts and machines.

2.2.2. Life cycle inventory analysis

For the development of the life cycle inventory, two possibilities are envisaged (Marx et al., 2020), namely top-down collection, i.e., through aggregated data on purchased materials and bottom-up collection, i.e., summing up the inventory data of single products or product clusters out of the company's portfolio (UNEP, 2015). In this O-LCA study a top-down approach was used.

Our study considers the whole process thus there is no need to solve the multi-functionality problem because the whole spectrum of outputs is included. The inventory includes the use and emissions associated with activities within the system boundary and is classified into direct activities and indirect activities. The following data are collected for the direct activities:

- Physical and chemical processing (i.e., reactions in EAF).
- Generation of energy resulting from combustion of fuels in stationary sources (i.e., billet preheating furnaces and boilers).
- Transportation of intermediate materials controlled by the reporting organization.
- Treatment of solid waste processed in the steel mill controlled by the reporting organization.
- Consumption of natural resources extracted with equipment controlled by the reporting organization (i.e., freshwater water).
- Emissions to air and discharges to water and soil from releases (i.e., evaporation of cooling water, air emissions).

It is emphasized that the data from direct activities also include all the processes required for slag processing and the subsequent production of the aggregate. The main data regarding the direct activities are reported in Table 1. Employee commuting, organization personnel travel, and client and visitor are excluded from this study because they are not priority, according to the prioritizing data collection process proposed by UNEP (2015). Supporting activities relating to the working environment are included, namely heating and air conditioning of workplace, and cleaning services.

The following data are collected for the indirect activities:

- Extraction and production of purchased:
    - o Raw materials (i.e., ferrous scrap, pig and cast iron),
    - o Fuels (i.e., natural gas),

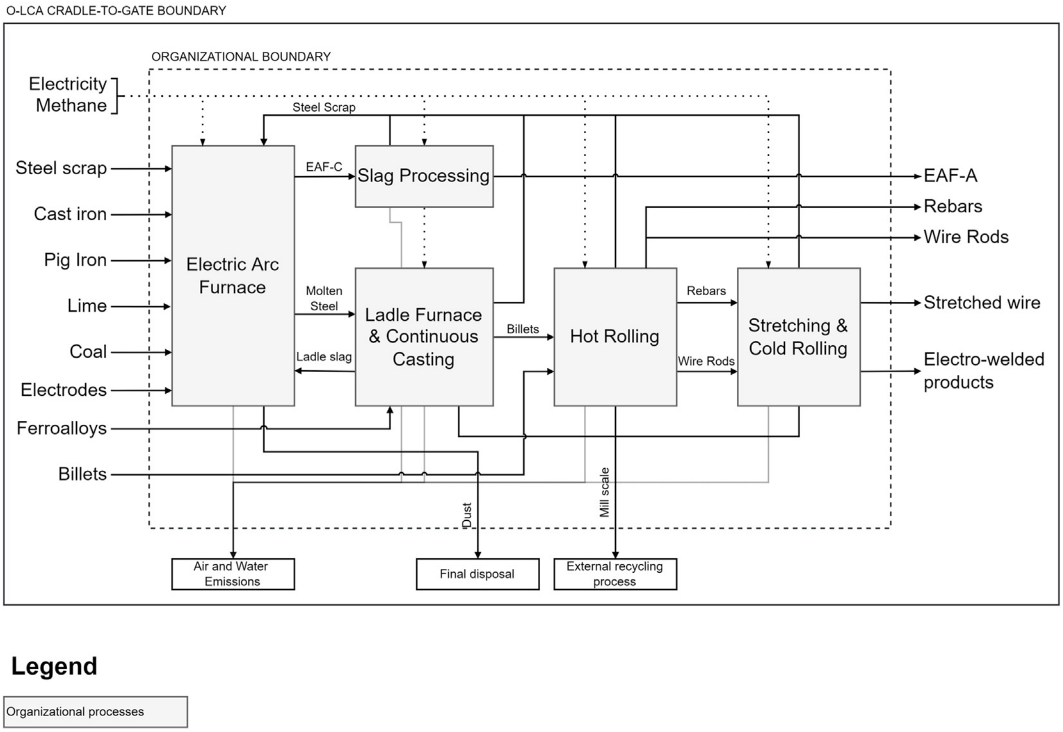

Fig. 1. System boundaries (O-LCA application).

  - o Goods (i.e., packaging and intermediate products),
  - o Outsourced services (i.e., handling of EAF-C),

- Extraction, production, and distribution of purchased electricity, steam and heating/cooling energy.
- Disposal and treatment of solid/liquid waste generated.
- Transportation of raw materials, fuels, goods and capital equipment (between suppliers and from suppliers), and waste.

Secondary data concerning the production processes of the materials and the disposal processes were obtained from the international database Ecoinvent 3.6. The main data regarding the indirect activities are reported in Table 2.

2.2.3. Life cycle impact assessment

The methodology chosen to evaluate the potential environmental impacts of the organization under study is the set of core environmental impact indicators reported in CEN (2019), which combines internationally recognized models such as ReCiPe (Goedkoop et al., 2009), Seppälä et al. (2006) and Boulay et al. (2018). This method permits to assess the environmental impacts of the organization by summing up the mass contributions of different input and output flows in the whole life cycle, multiplied for the characterisation factors. The environmental impacts were calculated according to Eq. (1) (Goedkoop et al., 2009):

$$I_m = \Sigma_i Q_{mi} * m_i \tag{1}$$

where m_i is the magnitude of intervention i (e.g. emissions released to air), Q_{mi} is the characterisation factor that connects intervention i with midpoint impact category m, and I_m is he indicator result for impact category m.

Table 1
Specific data of the steel plant under study (direct activities).

Input/output	Unit	Amount	Data source
Total steel production	Mt/y	1.6	Specific
Total aggregate production	Mt/y	0.21	Specific
Water withdrawal	m^3/y	1170993	Specific
Water discharge	m^3/y	410414	Specific
Emissions to air (CO_2)	t/y	185594	Specific
Emission to air (PM)	t/y	7	Specific
Emission to air (NO_x)	t/y	83	Specific
Emission to air (HCl)	t/y	12	Specific
Emission to air (other)	t/y	< 1	Specific
Emissions to water (Cl^-)	t/y	5	Specific
Emissions to water (nitric acid)	t/y	1	Specific
Emissions to water (other)	t/y	< 1	Specific

2.2.4. Scenario analysis (slag to landfill)

This analysis aims to explore the possibility to quantify the variations in terms of environmental impacts due to a different management of the steel slag and quantify the role of the steel slag treatment in the adoption of circularity practices. The appropriateness of this methodological step is confirmed by the utilization of the scenario analyses also in other LCA studies, particularly for waste management cases (Höjer et al., 2008).

The application of O-LCA, as described from Section 2.2.2 to Section 2.2.3 is adapted with some variations. With reference to the goal and scope definition, the reporting flow is modified, and in this case only steel products are considered, namely wire, rods, rebars, stretched wire and electro-welded mesh. The system boundaries include the same process reported in Fig. 1, with the exclusion of the steel slag treatment process, as reported in Fig. 2. The operations preparatory to slag disposal, the impacts of transporting and landfill disposal of the EAF-C are included. To describe the burdens occurring due to the landfill disposal, an Ecoinvent secondary dataset has been used (Slag, unalloyed electric arc furnace steel {RoW}|

Table 2
Specific data of the steel plant under study (indirect activities).

Input/output	Unit	Amount	Data source
Dusts	t/y	6300	Specific
Mill scale to recycling	t/y	27373	Specific
Refractory to recycling	t/y	7093	Specific
Oils to recycling	t/y	35	Specific
Waste transport by truck	ktkm/y	36	Specific

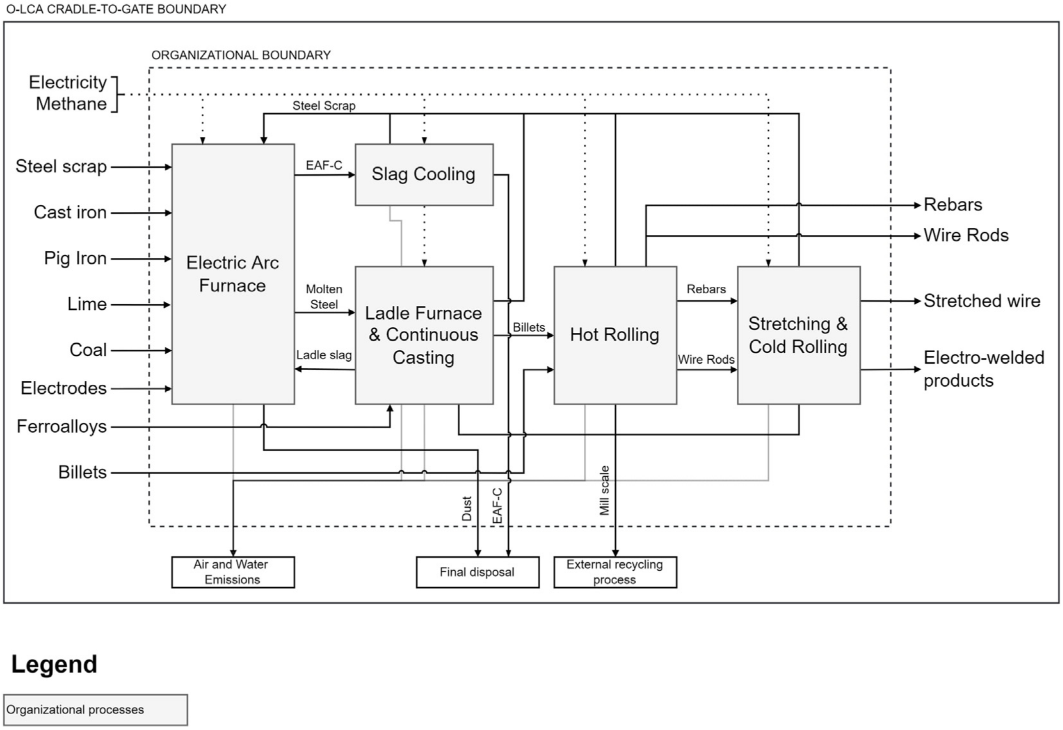

Fig. 2. System boundaries for the scenario analysis (O-LCA application).

treatment of, residual material landfill | Cut-off, U). The representativeness of the dataset was also confirmed by the similarity between the chemical composition considered in the dataset and the actual composition of the slag (prevalence of O, Fe, Si, Ca, Mn, Mg, Al).

2.3. Product Life Cycle Assessment (P-LCA)

The phases to perform a P-LCA study according to the ISO 14040 and ISO 14044 (ISO (International Organization for Standardization), 2020a; ISO (International Organization for Standardization), 2020b) are four: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation of results. Through the P-LCA methodology, the environmental benefits due to the circular economy practice of steel slag recovery is assessed form the perspective of the steel products.

2.3.1. Goal and scope definition

During this phase, the product under study is selected, namely the steel billet. The billet was chosen as the subject of the P-LCA application because it is the intermediate semi-finished product common to all steel products. The circular economy practice has no influence on downstream processes of billet production (continuous casting). The system boundary is therefore "cradle to billet", comprising raw materials extraction and transport to the steel plant, processes at EAF, ladle furnace and continuous casting, waste generated transport and treatment, internal transport of raw and semi-processed materials. Figs. 3 shows the system boundaries of the products under study. The declared unit chosen is defined as 1 t of steel.

2.3.2. Product life cycle inventory

For data collection, the year 2020 was taken as a reference period. The primary data collected were:

- materials used (quantity and type).
- transport of materials from the supplier to the steel plant (place of origin, type of the vehicle);
- mass and energy balances of the processes tacking place in EAF, ladle furnace, continuous casting;
- end-of-life scenarios and quantity of waste produced.

Specifically, with regard to the steel slag handling and treatment process, primary data were collected for: type of machinery and hours of use for handling; energy consumption for cooling, deferrization, crushing and screening processes; and water consumption for cooling (including qualitative characterisation of discharges). The secondary data, concerning the production processes of the materials and the disposal processes, were obtained from the international database Ecoinvent 3.6. EAF results in two co-products, steel and slag. As no exclusive flows can be identified for the two co-products, the impacts of the processes described below have been allocated according to an

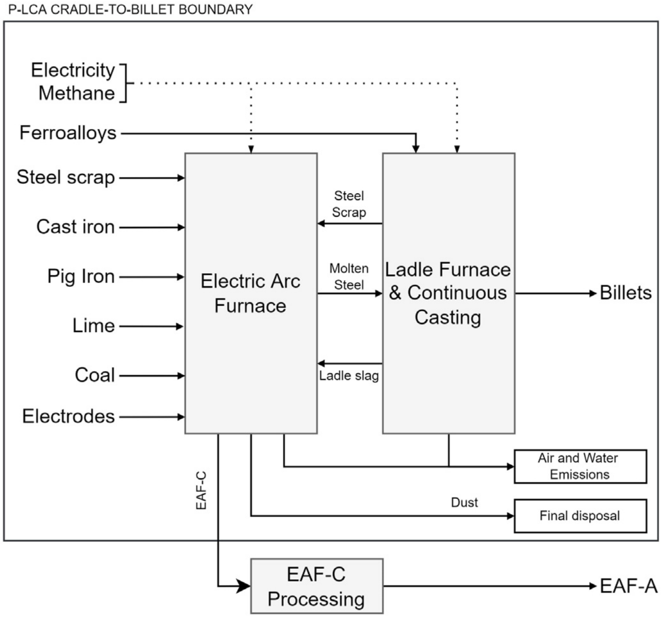

Fig. 3. System boundaries (P-LCA application).

Table 3
Specific data of the products under study.

Input	Unit	Amount	Description
CO_2	t	6.09E−02	Emission to air
Dust	t	2.44E−02	Landfill
Mill scale	t	2.03E−03	External recycling plant
Refractory (waste)	t	4.22E−04	External recycling plant
Dusts, VOC	t	2.04E−04	Emission to air
Water discharges	m^3	2.74E−01	Surface water body

economic principle and >99 % of the impacts are allocated to steel. The main primary data are reported in Table 3.

2.3.3. Product life cycle impact assessment

The method suggested by CEN (2019) is applied to perform the life cycle impact assessment, in line with the O-LCA application.

2.3.4. Scenario analysis (slag to landfill) for P-LCA

This analysis has the intent to explore the possibility to quantify the variations in terms of environmental impacts of the products under study due to a different management of the steel slag and quantify the role of the steel slag treatment in the adoption of effective circular economy practice on a product level. The production of the steel (billet) is analyzed and compared considering an alternative scenario in which the slag is landfilled.

To develop this analysis, the application of P-LCA, as described from Section 2.3.1 to Section 2.3.3 is adapted with some variations. With reference to the goal and scope definition, the declared unit is 1 t of steel, without considering the aggregate. The system boundaries include the steel slag cooling process, loading into vehicles, transport and disposal in landfills, as reported in Fig. 4.

With reference to the life cycle inventory, EAF-C is no longer classified as a co-product, thus no allocation is required, and the impacts for slag treatment and disposal are attributed to steel.

3. Results and discussion

The results obtained through the application of O-LCA are reported and discussed in Section 3.1. The results obtained through the application of P-LCA are reported and discussed in Section 3.2.

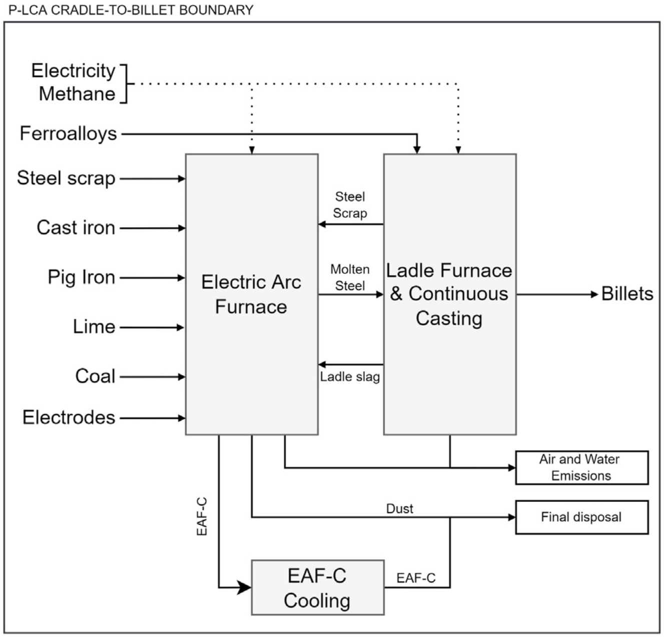

Fig. 4. System boundaries for the scenario analysis (P-LCA application).

3.1. Results of O-LCA application (slag recovery) and scenario analysis (slag to landfill)

The results of O-LCA application are shown in Table 4 (third column). Impacts arise mainly from upstream phases (raw materials production and transports), while activities carried out at the plant have contributions of <5.5 %. Only in the GWP-total and WDP impact categories activities carried inside the organizational boundary have a higher contribution, related respectively to CO_2 emissions (from methane combustion and reactions in the EAF) and to water withdrawals from wells. In all impact categories, except for ADP-minerals&metals, the most significant contribution is the production of electricity.

With reference to the processes that occur outside organizational boundary the following considerations can be drawn. For the GWP-total impact categories the main contribution is the electricity production, followed by the purchased billets and transports. Among the materials used, ferroalloys make the largest contribution, followed by cast iron and pig iron. Steel scrap, although it is by far the largest contributor in terms of mass, accounts for <1 % of the impact because it is a secondary material. The ODP impact category has a slightly different profile, with electricity still being the main contributor, but followed by methane extraction and distribution processes. The other most important contributions are the production of purchased billets and the transports. For the AP impact category, the main sources of impact are the electricity, transports (mainly due to emissions of transoceanic ships), external billets manufacturing, pig iron and ferroalloys production.

In the three impact categories related to eutrophication, very similar results are found for EP-marine and EP-terrestrial, while EP-freshwater shows some peculiarities. For EP-marine and EP-terrestrial, electricity contributes the most, followed by transports (mainly due to transoceanic ship), billets (16 %) and pig iron. For EP-freshwater, however, transport accounts for <4 %.

For the POCP impact category the main contribution is related to electricity production, followed by transport (mainly due to sea transport) and billets manufacturing. Among raw materials, pig iron and ferroalloys have a similar impact of 7 %, followed by cast iron.

The impact category ADP- minerals&metals is the only one where electricity is not the largest contributor (<10 %). For this category, impacts are mainly from externally produced billets, pig iron and ferroalloys. Transport is a significant contributor (15 %), particularly related to trucks' life cycle (10 %).

According to the ADP-fossil category, the consumption of fossil resources is distributed between the production of electricity, the external production of billets and the methane used at the plant. Fuel consumption for transport processes accounts for 6 %.

Finally, for the WDP category the largest contribution is electricity production, followed by purchased billets. In addition to the water consumption that occurs at the plant, as already mentioned above, the only other relevant contribution is the production of ferroalloys.

The results of O-LCA scenario analysis (slag to landfill) are shown in Table 4 (fourth column). The impacts are greater than those calculated

Table 4
Results of O-LCA application.

Indicator	Unit	O-LCA application (slag recovery)	O-LCA scenario analysis (slag to landfill)	% Variation
GWP-total	kg CO2 eq	1.257E+09	1.259E+09	+0.17 %
ODP	kg CFC11 eq	1.902E+02	1.919E+02	+0.9 %
AP	mol H+ eq	5.957E+06	5.989E+06	+0.5 %
EP-freshwater	kg P eq	2.747E+05	3.405E+05	+24.0 %
EP-marine	kg N eq	1.262E+06	1.273E+06	+0.9 %
EP-terrestrial	mol N eq	1.374E+07	1.386E+07	+0.9 %
POCP	kg NMVOC eq	3.990E+06	4.026E+06	+0.9 %
ADP-minerals&metals	kg Sb eq	5.801E+03	5.954E+03	+2.6 %
ADP-fossil	MJ	1.879E+10	1.888E+10	+0.5 %
WDP	m3 depriv.	3.100E+08	3.126E+08	+0.8 %

for O-LCA application (Table 4 third column) and an increase of the impacts ranging between +0.17 % to +2.6 % is obtained for almost all the categories (Table 4 fifth column) due to the disposal of the slag and the related transport. The category EP-freshwater is the most affected by the landfill disposal of the slag, showing an increase equal to +24 %.

3.2. Results of P-LCA application (slag recovery) and scenario analysis (slag to landfill)

The results of P-LCA application are shown in Table 5 (third column). Electricity represents the largest contribution in all the impact category, with the exception of ADP-minerls&metals category. The transport of incoming raw materials is a major contributor up to 25–27 % in the categories related to emissions of nitrogen oxides (EP-marine, EP-terrestrial and POCP) distributed among the three means used (ship, truck and train). Among the input materials to the EAF, pig iron contributes between 3 % (ODP) and 13 % (EP-terrestrial), with a peak of 23 % in ADP-mineals&metals. Ferroalloys, added to the smelting bath at the ladle inlet, contribute >5 % in all categories, with an average contribution of 10 %. Coal has a peak contribution in the ADP-fossil category, while methane contributes >1 % only in ODP and ADP-fossil. The incoming scrap recycling processes are always <1 %.

Among the processes related to the core phase, air emissions, water withdrawals and the management of generated waste are important contributors. Direct CO_2 emissions from methane combustion and reactions at the melting furnace contribute 12 % in the GWP-total category. Nitrogen oxides emissions, on the other hand, generate impacts in EP-marine, EP-terrestrial and POCP.

Well water consumption contributes 19 % in the WDP impact category. The management and disposal of waste generated at the plant always has a contribution of <1 %, with the exception of the ADP-mineral&metals category in particular for the transport and disposal of dust.

With reference to other studies of P-LCA application, the results calculated in this study can be considered in line with those calculated by Nidheesh and Kumar (2019) which quantified the impact on climate change equal to 766 kg CO_2 eq / t also including the processing after billets production and with the considerations drawn by Burchart-Korol (2013), which, in their study, highlighted that energy consumption causeed the greater impact for EAF plants. Considerations from Renzulli et al. (2016) cannot be taken as reference, since their application is focused on a blast furnace plant.

The results of P-LCA scenario analysis (slag to landfill) are shown in Table 5 (fourth column). The impacts are greater than those calculated for P-LCA with slag recovery (Table 5 third column) and an increase of the impacts ranging between +1.6 % to +43.1 % (Table 5 fifth column) is obtained due to the disposal of the slag and the related transport. The category EP-freshwater is the most affected by the landfill disposal of the EAF-C, showing the greater increase.

Our study is in line with the concepts revealed by Colangelo et al. (2018) and Colangelo et al. (2021) which has demonstrated that the environmental benefit improves as the percentage of recycled material increases, also considering the reduction in the amount of material to be disposed of in landfills for recycled aggregates from construction and demolition wastes.

Table 5

Results of P-LCA application.

Indicator	Unit	P-LCA application (slag recovery)	P-LCA scenario analysis (slag to landfill)	% Variation
GWP-total	kg CO_2 eq	5.100E+02	5.184E+02	+1.6 %
ODP	kg CFC11 eq	7.528E−05	7.729E−05	+2.7 %
AP	mol H+ eq	2.501E+00	2.547E+00	+1.8 %
EP-freshwater	kg P eq	1.041E−01	1.489E−01	+43.1 %
EP-marine	kg N eq	5.441E−01	5.584E−01	+2.6 %
EP-terrestrial	mol N eq	5.898E+00	6.054E+00	+2.6 %
POCP	kg NMVOC eq	1.715E+00	1.760E+00	+2.6 %
ADP-minerals&metals	kg Sb eq	2.112E−03	2.261E−03	+7.1 %
ADP-fossil	MJ	7.403E+03	7.546E+03	+1.9 %
WDP	m3 depriv.	1.224E+02	1.266E+02	+3.4 %

3.3. Comparison of variations

Table 4 and Table 5 show the comparison of the variations for O-LCA application and for P-LCA application. It emerges that the variations are similar for 8 categories out of 10 demonstrating that for these categories the differences are very similar both on organization and on product level and thus that the two applications, for our case study, can detect the efforts to recover the slag. For the category ADP-minerals&metals the variation is greater, and it is associated with the higher amount of metal and mineral raw materials needed if the slag is not treated. EP-freshwater is the category for which the two applications can detect the efforts to recover the slag with the greater difference, because it is affected by the emissions generated during the landfill disposal of the slag. However, even if the variations are similar for almost all the categories analyzed, it emerges that the variations obtained in the P-LCA application are greater than those obtained in O-LCA application, and this is due to the following methodological reasons:

i) for P-LCA application the input and the output flows are allocated among products and co-products, namely between steel billets and the slag which finally is processed to obtain an inert for the construction sector. Thus, the inert is a coproduct with input and output flows allocated. In the P-LCA scenario analysis the slag is treated as a waste and the input and output flows are all allocated to steel billets increasing their impacts. This aspect can only be perceived through a product perspective, while it is not relevant for the O-LCA.
ii) the system boundaries of the P-LCA do not include further processing of the billets, thus percentage values of variation are higher than O-LCA which is based on wider system boundaries.

4. Conclusions

The aim of this research is to assess the environmental improvements of a steel mill applying a specific circular economy practice, namely the recovery of the generated steel slag, through the O-LCA methodology, thus moving from the perspective of the product incorporating the steel slag, often investigated in the scientific literature, to the perspective of the plant generating the steel slag. In addition, this study explores to what extent the improvements and the efforts to recover the generated steel slag can be detected using an organization perspective, making a comparison with the more traditional product perspective. The case in which the steel slag is recovered is compared with the case in which the steel slag is landfilled using both O-LCA and P-LCA methodologies. From the obtained results it emerges that:

- the case in which the steel slag is recovered presents lower impacts than its landfill disposal through both O-LCA and P-LCA applications;
- the percentage variations are similar for 8 categories out of 10 demonstrating that, for our case study, O-LCA and P-LCA can detect the efforts to recover the slag;
- two categories, namely ADP-minerals&metals and EP-freshwater, are affected by the greater amount of metal and mineral raw materials needed if the slag is not treated and by the steel slag landfill disposal more significantly. They present the greater variations between the case in which the steel slag is recovered and the case in which the steel slag is landfilled.

In a wider perspective, this study explores the shift from a product perspective, more traditional and often investigated, to an organizational perspective. What the results tell us, based on this case study, is that:

- the variations obtained for this study in the O-LCA application are lower than those obtained in P-LCA application, and this is due to the application of the allocation procedures among co-products according to the P-LCA methodology and the width of the system boundaries.

- O-LCA methodology can detect the environmental improvements due to the application of circular economy practices, but the reduction of the impacts is less clear than P-LCA application.

This study contributes to improve knowledge about the application and environmental effectiveness of circular economy practices not only from a product point of view, but also by providing a complete picture of the environmental benefits from the perspective of the organization that generates the slag and of the main products realized in a steel mill. Although in this specific application O-LCA and P-LCA detected similar variations, it is revealed the two methodologies are not interchangeable. The application of O-LCA, although leading to lower differences between the cases analyzed, has the advantage of providing a measure of reductions with respect to the entire organization's impact. This is useful for setting and monitoring company-wide environmental impact reduction targets. The main limitation of this study is that a specific practice is explored linking the obtained results to the practices of processing or landfill disposal the steel slag, neglecting other possible circular economy initiatives. A further development of this study will be the analysis of the other circular economy practices, not only regarding the steel slag, including also other scraps generated by the steel mill and the exploration of other combinable aspects with a life cycle-based perspective.

CRediT authorship contribution statement

Sara Toniolo: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Alessandro Marson:** Data curation, Investigation, Formal analysis, Software, Writing – review & editing. **Andrea Fedele:** Validation, Visualization.

Data availability

The authors do not have permission to share data.

Declaration of competing interest

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

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