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Destination of the waste generated by a steelmaking plant: a case study in Latin America

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The purpose of this article is to identify the destination given by a steelmaking plant located in Brazil to the waste it generates. The research method is a case study. The primary research techniques are interviews with practitioners and scholars, visits to the steel plant and applications, and analysis of internal documentation. The main contribution is a complete case in a large company that generates a significant amount of waste. For each ton of steel, an ordinary steel plant generates approximately 0.6 tons of waste, such as steelmaking slag, electric arc furnace dust, mill scale, and zinc sludge. The slag routes to the conservation of unpaved roads, the electric arc furnace dust routes to Zamak manufacturers and earthworks activities, the mill scale routes to the cement and machinery construction industries, and the zinc sludge helps to produce new zinc ingots. The main obstacles for more elaborate destinations are the lack of research, logistics cost, and the need for environmental licenses.

1. Introduction

Increasing social consciousness and more rigorous legislation forced companies to modify the operation strategy of their supply chains (SC), taking into account not only economic but also social and environmental objectives (Chaabane *et al.*, 2011). More recently, focal companies and business partners of the SC assumed full legal responsibility for the disposal of industrial waste (Tang *et al.*, 2008). Since then, industrial waste recycling and reuse have helped companies reduce costs, comply with legislation, and still create a positive corporate image with their customers (Siddique, 2011; Siddique and Chahal, 2011). Companies whose manufacturing processes generate waste can return their residues to their production processes or route to other industries as raw material or fuel by reverse logistical channels (Sellitto, 2018). Reverse logistics practices can increase the useful life of public controlled landfills, reduce the extraction of new natural resources (Huang *et al.*, 2020), decrease the operational cost of industrial operations in the SC (Sellitto *et al.*, 2013), and help to supply small business and towns with excess energy (Butturi *et al.*, 2019).

Many kinds of SCs have incorporated closed loops in their inherent topology. Closed loops are circular flows of materials that require finding a new use for parts and products, recovering as much as possible of the original value of the good (Morioka *et al.*, 2013). Closed-loop supply chains (CLSC) incorporate systemic feedback elements in which waste from one industry replaces raw materials

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and energy sources in the same or other industries (Lyons *et al.,* 2009). The steel industry has characteristics that stimulate CLSC. Almost all products made from steel return to a melt-shop after the end of the useful life (Vadenbo *et al.,* 2013). Steel is the most important raw material for various industries (MacKillop, 2009) and the most recycled material in the world, which connects the steel industry with circular economy practices.

Steelmaking plants generate three main classes of waste: slag, powders, and sludge (Quaranta *et al.,* 2015). Many times, the low intrinsic economic value severely limits recycling, which forces companies to dump residual streams in controlled landfills or store them, waiting for a future opportunity for reuse. Therefore, steel plants need to find permanent applications to their residues (Lundkvist *et al.,* 2013).

Under this scenario, incorporated environmental responsibility actions and integrated ecological concerns into their management systems (Singh *et al.,* 2008). In Brazil, approximately 30% of steel comes from recycling. In 2017, Brazilian companies certified by the ISO 14001 management standard provided approximately 90% of the production and recycled approximately six million tons of metallic scrap. Not only metallic waste but also exhausting gases are intensively reused in steelmaking plants for heat recovery (Sellitto, 2018).

The purpose of this article is to identify the destination given by a steelmaking plant located in Brazil to the waste it generates. The research question is what are the possibilities to appropriately give a destination to the waste generated by a semi-integrated steel plant? The secondary objectives are (i) to identify the kind of waste generated by the plant, (ii) to identify the current destination, and (iii) to compare with the literature. The contribution of this study is to present the case of a reference company that produces a significant amount of waste belonging to an industry in which waste has strategic importance. The specific relevance is the fact that the company routes properly 100% of the waste it generates, no longer dumping at controlled landfills. For each ton of steel, a typical steel plant generates approximately 0.6 tons of waste (Motz and Geiseler, 2001). As the company produces more than 300.000 tons of steel per year, the routed amount is expressive. The policy substantially increased the useful life of local industrial landfills.

The research method is a single, qualitative case study. The structure of the current case study included two main steps. The first included a set of interviews with practitioners of the plant, a guided visit to the plant, and a documentation stage. The second included an analysis (interviews and visits) comparing the current destinations with the pertinent literature to verify the adequacy of the current destinations given by the plant to their waste.

Eckstein (1975) states that a case study can contribute scientifically, in increasing degrees of complexity: offering a specific description of an object, identifying regularities in similar objects, creating a situation to test a previously derived idea, jointly test a set of single, sparse ideas already tested in isolation to form a plausible basis for further research, and apply the crucial case, a unique case that will support or refute a derived hypothesis. The contribution aligns best with the joint test of single ideas previously tested. Optimizing models and quantitative analysis are beyond the current scope. This study does not handle alternatives or the decision-making process to route each kind of waste, which happened a few decades ago. This study only identifies and describes the current destination that the company gives to its waste. The rest of the article contains the review, research, discussion, and final remarks.

2. Background

2.1 Industrial Waste and Reverse Logistics Channels

Tsai (2010) classified industrial waste into hazardous waste and general industrial waste. Hazardous waste contains toxic substances with the potential to cause permanent damage. General industrial waste, usually composed of materials like plastics, food, rubber, paper, and construction leftovers, has less potential for environmental damage. The International Standard Industrial Code (ISIC) classifies waste into five risk levels considering its impacts on human health and the environment: serious threat, threat, limited threat, insignificant threat, and no threat (El-Fadel *et al.,* 2001). The Brazilian Association for Technical Standards (ABNT) classifies waste according to NBR10004/2004 in hazardous waste (Class 1) and non-hazardous waste (Class 2). Non-hazardous wastes can be Class 2A (non-inert waste) and Class 2B (inert waste). Inert waste is neither chemically nor biologically reactive and will not decompose over time.

Industrial waste management must follow a logical sequence. Companies avoid waste by changing product design to reduce loss. Industries such as wood, lumber, and metal-mechanic develop new products whose processes reduce leftovers using more effectively raw materials delivered in rolls, sheets, or plates (Sellitto, 2018). Moreover, the adoption of clean technologies minimizes the generation of waste. For example, in the same industries, higher-capability equipment reduces production failures that generate scrap. If it is not possible to eliminate or minimize waste generation, it is necessary to find return alternatives. In various industries, leftovers or spare parts serve as raw materials for new parts or fuel for endothermic processes. Finally, the residual material passes for proper treatment to become as inert as possible before routing to the ultimate residual disposition in controlled landfills (Marshall and Farahbakhsh, 2013; Valle-Zermeño *et al.,* 2015).

Table 1 describes the most relevant reverse processes for waste reuse.

2.2 Environmental role of the Brazilian steel industry

Steel is an alloy composed primarily of iron and carbon and represents the largest metallic category of industrial waste (EPA, 2018). The steelmaking process corrects certain iron impurities and adds other properties, such as resistance to wear, impact, and corrosion. Moreover, steel has a low manufacturing cost, which turns it into a major component in civil and mechanical construction. Steel ac-

Table 1. Reverse processes for waste reuse.

Process	Description	Main used references
Direct reuse	A used product receives a new destination, without repair, in an application that provides the same value (for example, a used vehicle).	Lippmann (1999); Wei and Huang (2001); Sasikumar and Kannan (2008)
Resale	A used product receives a new destination, in an application that provides lower value (for example, an urban bus designated for use in the agricultural activity).	Fleischmann *et al.*(2000); Daugherty *et al.*(2005)
Repackaging	A non-used returned product receives a new, updated package (for example, shoes and dresses not sold).	Rogers and Tibben-Lembke (2001); Chung *et al.*(2013); Sellitto *et al.*(2019)
Retrofitting	An obsolete product receives technological improvements to be updated again (for example, a manual lathe in which an automation unit replaces the control unit)	Fernández and Kekäle (2005); Vahl *et al.*(2013)
Disassembly	After separation, the components not damaged become spare parts for repair or return to the manufacturer (for example, computer and furniture components).	Cui and Forssberg 2003; King *et al.*(2006); Sellitto *et al.*(2017)
Remanufacturing	Parts retrieved and new parts build a new product, according to the original specifications and with the same expected performance (for example, industrial machines).	Tibben-Lembke and Rogers (2002); Kim *et al.*(2006); King *et al.*(2006)
Refurbishing	It is a process similar to remanufacturing, but with a lower level of work (only cleaning or repair of failed components in industrial machines).	Rogers and Tibben-Lembke (2001)
Recycling	It destinates waste, packaging, and returned products to manufacturers of a new product (for example, scrap tires to the cement industry).	Lee et al (2007); Sellitto *et al.*(2013); Sellitto and Hermann (2016)

counts for approximately 90% of all metallic materials consumed by the Brazilian industry (IAB, 2018).

The steelmaking industry uses four main technological routes: blast furnace, scrap melting, direct reduction, and smelting reduction (Szekely, 1996). The first route produces steel from iron ore and coke in blast furnaces (BF) and basic oxygen furnaces (BOF). The second produces steel from metallic scrap melted in electric arc furnaces (EAF). The third uses coal and natural gas to reduce iron ore and then feed it to EAF. The fourth route produces steel from iron ore without coke (Oliveira *et al.,* 2015). The melting temperature reaches approximately 1,450 to 1,550 °C (Zhang *et al.,* 2013).

In BF production, coal also acts as a reducer, associating with the oxygen of the ore and releasing the iron. The decarburization of molten iron yields molten steel. In the smelting process, impurities such as limestone and silica form the slag (Ayres, 1997). Successive burnings of impurities and additions of alloys and solidification complete the process. Steel assumes the form of ingots, blocks, billets, or slabs in a continuous casting (CC) machine. The next step is rolling, in which the steel is rolled to the specified shape and dimensions and transformed into products used by the industry, such as plates, coils, rebar, wires, profiles, bars, nails, and metallic screens (Sarkar and Mazumder, 2015).

The steel industry is an essential component for the integration of various SCs, due to its capacity to recycle almost all the metallic scrap generated by the mechanical industry and household consumption (Lundkvist *et al.,* 2013). The use of metallic scrap as a raw material reduces the consumption of nonrenewable virgin materials, such as coal, limestone, natural gas, and iron ore. It also reduces the need for disposal structures, increasing the lifespan of existing controlled landfills (Kumar and Sutherland, 2008). Finally, the use of recycled scrap saves significant amounts of energy and reduces the emission of greenhouse gases (Zhang *et al.,* 2013) because it renders unnecessary processing of virgin ore, which is inherently polluting and energy-intensive (Ayres, 1997).

The steelmaking process intrinsically generates an expressive amount of waste. Given the possibility of reward, some kinds of waste, such as slags, are sometimes considered more than waste, but by products (Motz and Geisler 2001). In developed countries, the production of one ton of steel implies approximately 0.55 tons of waste, mainly coke, coal, and EAF dust, BF, EAF, and CC slag, mill scale, various types of metallic scrap, various types of sludge coal fly ash, and refractory wastes (Sarkar and Mazumder, 2015). Bearing in mind exclusively slag, whose production accounts for 7.5 to 15 % of the produced steel (Anastasiou *et al.,* 2017), Europe generates approximately 18 million tons per year. Only 6% of the total waste dumps to landfills (Andreas *et al.,* 2014).

In 2014, the USA generated 259 million tons of municipal solid waste (MSW), which included 23.3 million tons of metallic waste, representing 9% of the total. Metallic waste represents approximately 7% of the total annual MSW generation (EPA, 2018). As the relationship between produced steel and waste is approximately 0.6, from a conservative perspective, if the current steel production only replaces the obsolescent material, it is plausible to assume that the waste generation of the steelmaking industry accounts for 4% of the total solid waste generated in the USA.

This study focuses mainly on the Brazilian steelmaking industry and its eco-efficiency. Brazil launched in 2010 its National Solid Waste Policy (PNRS). The primary objective of this policy is to internalize environmental costs and liabilities for manufacturers and consumers, establishing and promoting integrated reverse logistics actions. PNRS sets the principles, goals, instruments, and guidelines related to solid waste management, turning companies responsible for the waste they generate. The law also created shared responsibility for a product throughout its entire lifecycle. The responsibility extends to manufacturers, importers, distributors, traders, consumers, and public service holders. PNRS defines reverse logistics as an instrument of economic and social development that enables the collection and return of solid waste by local reuse, recycling to other companies, or final appropriate disposal in controlled landfills (Jabbour *et al.*, 2014).

The Brazilian steel industry currently occupies the ninth position in world steel production ranking and is made up of 14 private companies, controlled by eleven different holdings operating 30 plants in 10 states. Brazilian plant locations can be found at http://www.acobrasil.org.br/site2015/parque.asp. In 2017, the produced steel was used in the civil construction (38%), manufacturing of machines (21%), automotive industry (20%), appliances (7%), pipes (5%), packaging and other applications (5%) (IAB, 2018).

Steel products manufactured in Brazil can be classified by the type of steel and geometric form. Regarding the type of steel, the products can be carbon steels or low alloy, special or alloyed steels, steels for mechanical construction, and fast steels. As for the geometric form, the products can be semi-finished (plates, ingots, blocks, or billets that will be destined for other purposes, such as forging), planes, in which the width is much greater than the thickness (plates and coils), and long, whose cross-sections are polygonal in shape and the length is much larger than the section (bars, rebar, rails, tubes, wires, etc.) (IAB, 2018).

In 2017, Brazilian companies produced approximately 34 million tons of steel, used approximately 42 million tons of iron ore and 14.4 million tons of coal, and recycled approximately 9.2 million tons of metallic scrap. The industry operated approximately 850 thousand hectares of reforestation areas for charcoal production and 350 thousand hectares of legal and voluntary preservation areas. The industry spent approximately 9.9 GWh of purchased and approximately 9.8 million MWh of own-generated electricity, 84% of which was generated by the reuse of gases. The industry used approximately 5.9 billion cubic meters of water, recirculating 95% of this volume. Only 258 million cubic meters were collected from local hydrographic basins (IAB, 2018).

Over the years, the Brazilian industry has increased its eco-efficiency, mainly through integrated programs for energy conservation, reuse of gas, recirculation of water, and recycling waste and by products. The 30 companies invested approximately $ 800 million in environmental protection and development actions in 2014 and 2015. Approximately 60% of the investment focused on environmental control and energy efficiency and approximately 40% on environmental management. In 2017, the entire industry produced almost 21 million tons of waste dumping approximately 5% to landfills. In the same year, economic applications, such as cement manufacturing and concrete products, aggregates for civil engineering and road construction, fertilizers and soil correction for agriculture, landfill leveling or covering, and earthwork activities, use approximately 88% of the waste. By the time, the remaining part was in stock waiting for an ultimate destination (IAB, 2018).

In some issues, the environmental performance of the Brazilian steelmaking industry is more similar to that of developed nations than those of emerging markets. The Brazilian steelmaking industry produces approximately 0.60 tons of waste per ton of steel (IAB 2018). India produces approximately 1.2 (Sarkar and Mazumder, 2015) to 1.6 (Sharma *et al.*, 2017) per ton of steel, whereas developed countries achieve up to 0.55 tons per ton of steel (Sarkar and Mazumder, 2015). The Brazilian steelmaking industry recycles approximately 88% of the waste (IAB 2018). USA recycles approximately 90% (AISI 2018), Sweden approximately 80% (Jernkontoret, 2017), and India approximately 37% (Sarkar and Mazumder, 2015).

2.3 Related Studies

The literature presents many recent studies that reuse applications of waste dispensed by steelmaking plants, such as raw materials for the metal-mechanics industry, roads and railroads construction, and maintenance, building industry, ceramic industry, cement industry, agriculture and animal husbandry, and chemical industry. We highlight some studies. Chand *et al.* (2016) reviewed the profitable applications of slag as ballast in road construction services. Koh *et al.* (2018) applied slag as ballast for services in railway maintenance. Quaranta *et al.* (2015) applied slag and dust in the ceramic industry in bricks shaped by extrusion. Liapis *et al.* (2018) and Anastasiou *et al.* (2017) applied slag in civil engineering services to produce industrial pavements, heavyweight concrete, and pervious concrete pav-

Table 2. Studies on the use of steelmaking waste or byproducts.

Studies	Waste or Byproduct and Application
Siddique and Bennacer (2012); Delong and Hui (2009); Dong *et al.*(2013); Bernardo *et al.*(2007); Wang *et al.*(2013); Yi *et al.*(2012); Tsakiridis *et al.*(2008); and Monshi and Asgarani (1999); Kim *et al.*(2015)	Steelmaking slag in cement manufacturing
Shen and Forssberg (2003); Jones *et al.*(2002); Teo *et al.*(2014)	Steelmaking slag in metallic and ceramic recovery
Andreas *et al.*(2014); Wu *et al.*(2007); Ahmedzade and Sengoz (2009); Yi *et al.*(2012); Sorlini *et al.*(2012)	Steelmaking slag applications to leveling or covering landfills, and road and railway conservation and construction
Stolaroff *et al.*(2005); Bonenfant *et al.*(2008); Zhang *et al.*(2013)	Steelmaking slag for carbon sequestration, forming stable carbonate minerals (CaCO3).
Spengler *et al.*(1997); Shawabkeh (2010); Sturm *et al.*(2009); Dominguez *et al.*(2008); Salihoglu *et al.*(2007)	EAF dust in the zinc and cement industry
Vargas *et al.*(2005); Machado *et al.*(2011); Quijorna *et al.*(2011); Quijorna *et al.,* (2012)	EAF dust in the manufacturing of building materials as cement artifacts, tiles, and bricks.
Seh-bardan *et al.*(2013)	EAF dust in agriculture
Al-Otaibi (2008); Shatokha *et al.*(2011)	Mill scale applications in sintering and cement industry
Singh e Row (1981); Rabah and El-Sayed (1995); Jah *et al.*(2001)	Zinc sludge in the manufacture of zinc ingots

ing blocks. Husgafvel *et al.* (2016) applied rolling mill waste (powders and sludge) in soil amendment, low-grade concrete, and as mine filler. Montedo *et al.* (2015) produced glass-ceramics from mill scale. Guerrini *et al.* (2017) applied steel mill slag to soil correction. The applications counted on specificities in the processes. Further research should determine if they apply to other manufacturers.

Some articles not published in English report research done in South America. For example, Brassioli *et al.* (2009) and Correa *et al.* (2008) studied the use of steelmaking slag as a corrective of acidity in planting sugar cane and soybean in Brazil. Melloni *et al.* (2001) and Santos *et al.* (2006) studied the use of electric arc furnace (EAF) dust in the production of soybean and corn. Della *et al.* (2005) and Ferreira and Zanotto (2002) studied the recovery of ceramic materials from steelmaking slag. Pereira *et al.* (2011) investigated the use of mill scale (or oxide scale) from billets in cement manufacture. Table 2 summarizes other studies, not yet mentioned.

3. Methodological Concerns

The research method is a case study. The research methodology was:

- Interviews with four practitioners of the steelmaking plant (manufacturing, supply chain, environmental, and sales managers), visit the plant, and analysis of the available documentation. This step produced a list of amounts, characteristics, and current waste destination, complying with specific objectives (i) and (ii); and
- Panel with a sales practitioner of the steelmaking plant, two scholars with research and expertise in the reuse of industrial waste and two practitioners of secondary markets and a visit to applications. This step produced a comparison between the current destination and possibilities retrieved from the literature, complying with the specific objective (iii).

Triangulation among the four respondents and a guided tour in the plant ensures construct validity (Auerbach and Silverstein, 2003). A comparison with pertinent literature ensures internal validity (Maxwell, 2006). The use of a research protocol, face-to-face interviews, and double-check by respondents assure reliability (McCutcheon and Meredith, 1993). This study does not aim at external validity, which is an objective of further research involving more than one plant.

4. Results

4.1 The Waste

The studied company is a semi-integrated Brazilian steel plant that produces billets, blooms, bars, skelps, rods, angles, channels, joists, wires, and nails, among many other products to construction, industry, and agriculture applications. There are two technological routes for steel production: with the majority use of iron ore (integrated plants) and with the majority use of metallic scrap and pig iron (semi-integrated plants). Integrated plants operate with three stages of production: reduction, refining, and conformation. Semi-integrated plants operate with refining (in melt shops) and conformation (in rolling mills) stages.

Refining begins at the scrap yard. Electric drive scrap handlers and balance cranes with magnets help to inspect, clean, weigh, sort, and move to bays. Moving cranes pick the metallic load in bays and supply EAF, which transforms scrap and pig iron into molten steel. After the fusion, the liquid steel routes to a ladle furnace (LF) in which, combined with alloys, meet the chemical specifications and the required temperature for casting. The molten steel casts in cooling lines, forming billets and blooms, which are the final products of the melt shop. The EAF and LF operations generate powdery metal emissions, exhausted and deposited by extensive dust collection systems, usually composed of electrostatic precipitators and sleeve filters. The precipitation forms the so-called EAF dust.

The conformation starts at the mill rolling shop. The billet reheated at 1000-1200 °C passes through rolling mills, which reduces and modifies the section until reaching the desired profile. The lamination process generates a layer of oxide on the billet, which is the mill scale. There is a second conformation stage, cold drawing, in which a process of cold mechanical conformation occurs. The material undergoes a mechanical stripping process to remove the grease. The wire rod undergoes an annealing process to increase dutibility and by a zinc bath galvanizing process to protect against oxidation and improve the physical appearance. The galvanizing process generates zinc sludge.

The waste of the steelmaking plant comprises slag (waste type 2A), EAF dust (type 1), mill scale (type 2A), and zinc sludge (type 2A). The company does not get any payment for the slag. The company receives payments for EAF dust, the mill scale, and the zinc sludge.

Steelmaking slag is an ionic solution consisting of oxides (such as FeO, CaO, MnO, SiO_2, P_2O_5, Fe_2O_3, and MgO) and fluorides (CaF_2) floating on the surface of the liquid steel. Slag is helpful in the steel production process because it protects refractory liners against high temperatures, absorbs deoxidation products and inclusions, accelerates the dephosphorylation and desulfurization process, protects the steel against oxidation and absorption of nitrogen and oxygen, and reduces thermal losses. The operation generates approximately 12,000 tons of slag per month. The steel plant donates the slag to an outsourced company with a more extensive scale of production, which makes the business feasible. Otherwise, the steel plant would achieve a negative economic result in managing and handling waste. The outsourced company removes the waste from the melt shop, processes it in a crusher, and sells it in secondary markets, mainly for the conservation of local unpaved roads.

Regarding the EAF dust, a dust collection system filters the metallic emissions of the furnaces and retains it, which avoids the release into the atmosphere. EAF dust is composed of oxides of iron, zinc, calcium, magnesium, and silica. It has fine granulometry, generating approximately 200 tons per month. The main applications are raw materials for the production of Zamak alloys and earthwork activities in the building industry.

Table 3. Synthesis of the situation of waste or byproducts in the steel plant.

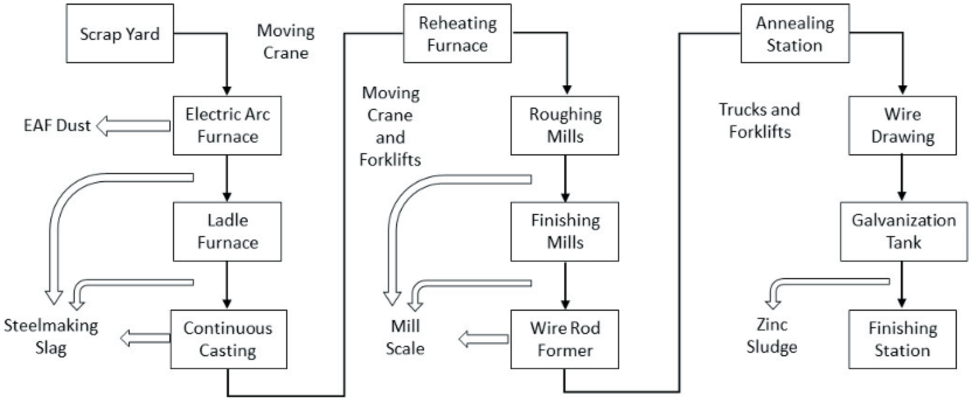
By-product	Class (ABNT)	Composition	Production per month	Current destination
Steelmaking Slag	2A	Oxides and fluorides	12,000 tons	Maintenance of local unpaved roads
EAF dust	1	Oxides	200 tons	Zamak alloys manufacturing, earthwork activities
Mill Scale	2A	Iron oxide	200 tons	Cement industry as a chemical corrective; Machinery industry, as the counterweight of elevators
Zinc Sludge	2A	Approximately 80% of Zinc	30 tons	Zinc ingots manufacture

The mill scale is a type of metallic surface, a residue due to the oxidation of the steel surface, formed by oxides of iron, silicon, aluminium, and calcium. The scale appears in the continuous casting and rolling mills reheating furnaces. If not removed, it damages the quality of the final product. The operation generates approximately 200 tons per month. The main application is chemical corrective to the cement industry. Second, the waste serves the machine-building industry for the construction of counterweights of elevators.

Zinc sludge results from the galvanizing process and contains approximately 82% of Zinc. If not removed, it causes damage to the aesthetic appearance of the galvanized wire. The sludge is a thermal insulator that increases thermal efficiency. The operation generates approximately 30 tons per month. The sludge returns as a partial feedstock to the manufacturers of zinc ingots that also supplies the plastic, glass, and rubber industries. Table 3 synthesizes the findings.

Figure 1 illustrates the waste formation and destination in the steel plant.

Figure 1. Waste generated by the plant



Compared with the company's annual billings, the revenue from recycling has little significance, approximately 1.2 million US dollars per year. The main motivation is to give an adequate destination for the expressive volumes generated and to avoid the maintenance cost of controlled areas. Because the volumes are large and options are few, the company has an insignificant margin to bargain.

4.2 Comparison with the literature

The next step included a panel of scholars and experts in reusing waste and practitioners of secondary markets. The main objective of the panel was to compare the results with the possibilities retrieved from the literature and analyze the feasibility of the applications in the case of the studied steelmaking plant.

Regarding steelmaking slag, the applications the literature reports the use of raw material in the cement industry, recovery of metals and ceramic materials, leveling or covering landfills, conservation, and construction of roads and railways (as surface layers or road bases), carbon sequestration, and agricultural activities. The only application entirely explored by the studied company is the maintenance of local unpaved roads. The quantity and demand for conservation services in railways in the region are low. The other forms require further research. Due to the low price and lack of research, more elaborate applications are still unattractive. The use in the cement industry implies high logistics cost because the material requires previous handling, mainly an additional comminution process and a transportation operation as well as safety concerns all over the entire process. The economic recovery of ceramic or metallic materials as well as carbon sequestration requires further research because of the specificities of the local EAF dust. The local secondary market for leveling and covering landfills is low, so it is also not attractive. Agricultural applications are also unattractive, requiring further research and environmental licenses, usually expensive and time-consuming. As road maintenance services fully absorb the overall amount, unavailability discourages new, higher-value applications. An extensive program of complementary research should turn the waste more attractive to higher-value industries and applications and eventually increase the price.

Regarding EAF dust, the literature indicates applications as a raw material in the cement, zinc, and ceramic industries, in the manufacture of Zamak, in earthworks, and soil correction for agricultural activity. Of these possibilities, the only viable applications are the production of Zamak and the use of earthworks in the civil engineering industry. As the selling price and amount are low, more elaborate applications are limited. The cement industry requires further research because of chlorine, which damages the liner of the clinker kilns and harms the environment. The zinc industry usually requires payments to receive and apply the waste. Currently, the local ceramic industry is highly hostile to workers. EAF dust handling would make the social environment still worse. Agricultural applications require further research and environmental licenses, usually expensive and time-consuming in the region, which makes their use unattractive.

Regarding the mill scale, the literature indicates its use as a raw material for sintering processes and the cement industry. Applications in sintering are limited by distance, as the Brazilian integrated steel plants are located far away from the studied plant. Furthermore, future implementations require complementary research because of the specific characteristics of Brazilian ore. Therefore, the supply is entirely available to the local cement industry.

Finally, regarding zinc sludge, the main possibility retrieved from the literature is reuse in the manufacture of zinc ingots. As it occurs with the mill scale, the plant has already entirely explored this possibility.

Table 4 summarizes the main limitations and obstacles found in the study for the entire exploration of the applications retrieved from the literature. We observe that the company achieved in full its primary objective, the prevention of severe environmental impact. Economic goals have secondary importance in this case.

The major obstacles to further, higher-value applications are the need for complementary research, the logistical cost, and the need for environmental licensing.

Table 4. Obstacles for the application of waste from the plant.

By-product	Application	Obstacle						
		environmental licensing	logistics costs	more research	no demand in the region	requires payment	safety problems	Currently feasible?
slag	agriculture	x	x					
	cement		x	x				
	recovery			x				
	sequestration			x				
	roads							yes
	railways				x			
EAF dust	cement			x				
	zinc					x		
	ceramic			x			x	
	Zamak							yes
	earthworks							yes
	agriculture	x		x				
mill scale	sinter		x	x				
	cement							yes
	machinery							yes
zinc sludge	zinc ingots							yes

5. Conclusion

The purpose of this article was to identify the destination given by a steelmaking plant to the waste it generates. Steelmaking plants generate slag, powders, and sludge. The totality of the waste receives a proper destination. Slag routes to maintenance services in local unpaved roads without retribution. Powders (EAF dust and mill scale) route to manufacturing activities such as Zamak alloys, cement, and machinery fabrication as raw materials. Powders also route to earthwork services. The company receives a fee. Finally, the sludge routes to zinc ingot manufacture as a raw material. The company also receives a fee. Regarding the slag, the benefit is not to pay the costs of handling and disposal. In other cases, in addition to meeting an environmental objective, the company receives revenue.

Although economic retribution is not large, the environmental and social effects of reuse are expressive. The plant generates more than 12,000 tons of waste per month without dumping, whereas in the Brazilian steelmaking industry, approximately 8% of the waste routes to landfills. The most important social effect is that an environmental-friendly, clean production company, located in a metropolitan area inhabited by 4,000,000 people circa, operates a major technological and economical complex that provides many qualified jobs and pays an expressive amount of taxes. In short, the reuse of the waste turns viable the economic activity of the company in the center of a densely populated region. In particular, the company sponsors programs on public health services, public education, and order forces, which directly contribute to the life standard in the region.

Finally, regarding the territorial appraisal, the main implication of the zero-dumping policy is that the surrounding area passes by a rapid appreciation of the territory. At the same time, the region reduces externalities and hosts an important industrial complex that generates jobs and income opportunities. Areas originally designated to receive waste can now receive new projects, either industrial, residential, or agro-industrial. A river around the industrial complex has resumed its economic importance due to the now possible access to the riverside area. In short, the reduction of externalities enables new opportunities to exploit a territory within a densely populated area. A comprehensive description of this case is the main contribution of this article.

As further research, we suggest a survey of all companies in the Brazilian steelmaking industry to gain a broader profile on the reuse and destination of waste. We also suggest in-depth case studies with other successful companies and the implications of reuse and recycling on other companies. We recommend the use of quantitative data for historical series analysis (for instance, the historical correlation between the amount of production and the amount of reused or recycled waste). Finally, we propose a specific case study on the utilization of the mill scale in the machine-building industry, as this application did not appear in the literature review.

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