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Steel, Material Flows, and Globalisation: by-product Optimisation and Waste Management in today's steel industry

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Abstract – This paper, delivered at the SAM2 Conference in Nantes, France, in April 2008, addresses issues of material flows in a selection of modern steel plants, especially the generation of wastes, from a social sciences perspective. I analyse key factors structuring waste management decisions through the case of "problem" wastes arising at a steel company's plants. I discuss how some materials come to be construed as more problematical than others from a material and technological point of view, but also by taking into account organisational and legislative issues, in order to show that the construction of the "waste" category needs to be envisioned as resulting from a matrix of socio-material causes.

The steel industry has undergone profound corporate changes of late with high profile takeovers that are part of a shift from the West to developing countries of the centre of gravity of the industry. This change is also illustrated by the rapid rise of China (and, increasingly, India) both as a consumer and producer of steel, and its increasing importance on the market for raw materials. Steel is probably the material of the globalised world and its icons (the aeroplane, the cargo ship, the automobile), it is extremely flexible in its applications, and fits into the current discourse on "sustainability" because it is recyclable. However, paradoxically, steel is more or less absent from research agendas in the social sciences: it tends to be neglected as an "old", "dirty" industry that has nothing to teach us and that we have nothing to say about. In this paper, I show that this industry can tell us a lot about the social, economic and environmental aspects of the transformation of materials and the production of wastes in the context of globalisation. This industry offers an opportunity to visualise flows of materials and their fates and connect them to the overarching dynamics structuring our world today. Likewise, I hope to show that the industry can also benefit not just from the raw input of technology, but also from a more reflexive approach supported by research in the social sciences: in other words, I would like to make the case for greater collaboration between industry and the social sciences.

I start with an overview of the steel industry and the production of steel, in order to frame the reflection in terms of flows of materials, and show how this can be formalised to convey the complexity of the processes involved in the industry, and the parts of the process where materials can become wastes. Then, in a second part, I focus on specific materials that have come to be seen as problematical certain segments of the steel industry[1]: how and why do some materi-

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[1] Due to the sensitive nature of some of the information and in order to comply with the ethical requirements of academic research, the results presented here are strictly anonymous. Research, including interviews of executives and shop-floor personnel, was carried out at several major steel plants of different companies in Europe and Asia, and complemented by interviews with steel industry experts and a comprehensive literature review to put these data in global perspective. Many of the issues addressed here apply to some degree to the global steel industry, so the preservation of the anonymity of sources of data is not believed detrimental to the reader. All ideas

als become "problem wastes"? What does this tell us about wider dynamics of material flows and the social construction of the "waste" category? Ultimately, what does it reveal about the factors structuring by-product and waste management in the industry today?

1 Part I: the steel industry: material flows, production, and wastes

In this first part, I build a model of the steel industry today in order to understand flows of materials, as well as production, by-products, residues, and wastes.

Beyond steelmaking *stricto sensu*, there are other activities involved in the process of making steel, each with their by-products and wastes. For instance, cokemaking, with its associated dusts and gases, and the generation of large quantities of coke fines, as well as flows of contaminated water. There is also sintering, which generates highly toxic dusts and where dioxins are also a concern. Therefore, simply analysing the steps of steelmaking itself is not enough to understand the full impact of the production of steel or to get a complete picture of waste management in the industry. However studying all these aspects would be too vast an enterprise, so, while acknowledging these steps of the process and their contribution to overall waste production, I focus on the most problematical points of the production process, both within and without the steelmaking process itself.

1.1 Materials and their fates: formalising flows

I focus here on what happens to the materials in the production of steel: how they are transformed into products, by-products and wastes, based on the mass balance principle of "what comes in must come out".

(a) The examples of the coke ovens and the sinter plant

Let us look at two crucial steps of steelmaking, to identify what exactly is produced in each of these steps. By produced, I mean not only the desired (aimed-for) material at each step of the process (sinter, liquid iron, steel etc.) but also the by-products of each step, which, depending on whether it is reused or not, can, *de facto*, become "waste", or start to migrate towards that category, via treatment, storage etc. For the moment, the widely accepted definition of waste suffices: "a substance that a given agent does not, or does not intend to, reuse in the forseeable future". Thus, stockpiling, even under the pretense of "future" use, will be considered waste when that "future" use is not clearly defined given today's technologies.

First, the coke plant. Coke is produced from the destructive distillation of coal at high temperatures. Large quantities of gases are emitted, namely CO (carbon monoxide), CO_2, SO_2, NO_2 etc. However, a lot of this gas is actually reused, either at the coke plant itself, or circulated to other parts of the steel plant, such as the blast furnace (BF). CO, for instance, is burnt to produce the heat required. Also, large quantities of dust arise from the production of coke; however, a considerable proportion of this extemely abrasive coke dust is reused via the sinter plant.

The sinter plant combines ore, coke and lime in sintered pellets that can be fed into the BF to enhance and stabilise its operation, ensuring optimal hot metal quality. The sinter plant produces large quantities of gases and toxic, heavy-metal-laden, dusts. However, the sinter plant also acts as a "recycling" plant: dusts from other parts of the production process (cokemaking, BF, BOF (basic oxygen furnace), rolling... as well as dusts generated in the sinter plant itself), as long as they contain Fe (iron), C (carbon) and/or fluxing agents, can be recirculated in the sinter strand, thereby contributing to loop closure. Thus, although the sinter plant itself generates a lot of dusts, they are mainly reused in the sintering process, and the sinter plant can take on a lot of the by-product burden of the whole plant, as will be seen in more detail later.

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within the paper are the personal opinion of the author and are not sanctioned by any institution, organisation or other third party, and specifically not the University of Southern Queensland.

Therefore, such processes, although they do generate wastes and emissions and can be a concern, will not be the focus here, because they witness a lot of recirculation of their products in other parts of the process, and thus do not really pose a problem overall.

A more abstract way of looking at the flows of materials in steelmaking goes like this: what (typically) enters a steel plant and the various parts of the production process, and how material flow from one part to another. This is the Material Flows Analysis (MFA) grounded in industrial ecology,: What average quantities of materials are produced at each step of the process? How do they circulate between different parts of the process? And how much eventually ends up in the "waste" category, after having been a raw material, a by-product, or a residue? Indeed, a discussion of all these potentially confusing terms is necessary to understand how and why waste becomes waste – the "biography" of waste –, through which steps, and how this is subject to historical and spatial variations linked to technologies, techniques, practices, but also the very material characteristics of the "stuff" of steelmaking.

(b) Typical flows at plant level

The following diagram ("Typical flows in a steel plant") shows the flows of materials from the different parts of the process, for a typical steel plant. It clearly shows both the recirculation and the loss of materials in the production process. What we notice with this diagram is the variability (or the fuzziness of our knowledge) of flows for some materials, and the stability (or more precise knowledge) of others. For instance, the production of BF slag appears to be stable at 240 kg per tonne of crude steel, in any given plant, whereas the reflow of sinter, an essential aspect in our understanding of loops in the production process, varies from 275 to 550 kg per tonne of crude steel, a very wide margin indeed, reflecting varying practices in steel plants, but also probably the difficulty in tracking such dynamics. Indeed, what comes "out", such as slag, and ends its cycle there (and especially more so when it is, such as slag, a valuable and almost readily saleable commodity), is easier to account for than materials that "pop in" and "pop out" of a process, with series of losses, gains, and combinations that entail complex material changes. Such a complex process is evident in the case of the various gases, subsequently transformed in the treatment process into liquids (sludges) and solids (dusts, filter cakes). We can expect important losses in such a conversion process, and indeed, the figures for the production of these residues vary considerably, emphasizing a sort of fuzzy accountability when it comes to unwanted and (up to recently at least) unvalued materials that were traditionally candidates for a holes-in-the-ground end: thus, the quantities of waste are also a function of society's interest, or lack thereof, in certain materials.

1.2 Conclusions of part I

We have seen in this section, albeit in a very summarised form, how important it is to visualise the prodution of steel as a series of flows and counter-flows. Contrary to the assumed vision of production in general whereby material flow in one direction (from the "beginning" of the process to its "end", i.e. finished steel) we see that these flows often form (more or less closed) loops, with materials returning to "earlier" stages of production: thus, there is a fair deal of "recycling" in the very literal sense of things being recirculated, in cycles. In that sense, a lot of by-products do not become waste. Also, the transformations are numerous and multifaceted, with materials going from solids to fluids to gases, with all the transformations and losses attributable to entropy, making it arduous to precisely track everything that is going on. However, we can zero in on some specific points of the process where some materials end their course, for a variety of reasons, thereby becoming, for all intents and purposes, wastes.

2 Part II: identifying and analysing "problem" wastes in the industry

2.1 What makes a material "problematical"?

In this second part, I look at the factors structuring the way selected wastes are pro-

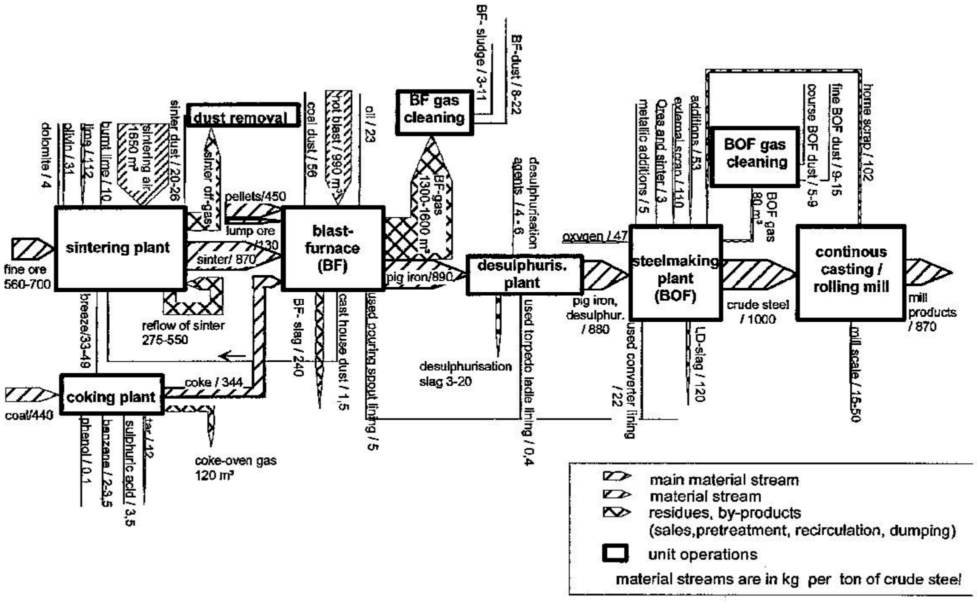

Fig. 1. Source : Geyer et al. [1, 2][3]**.**

duced, conceived, and managed in the steel industry today, and how those materials are framed, discursively and in practices, as "problem" wastes.

We have already seen that many by-products are re-used, sometimes almost entirely, in other parts of the process, and are therefore not to be considered wastes; the sinter plant is one of the main foci of this recirculation. There have also been other developments in this field, such as briquetting, whereby pellets can be produced from various dusts and sludges and then be used in the BOS plant both as a raw material and a coolant. Thus, the term "waste" is not actually applicable to many substances that were once seen as such, as they are put to use either in the production process or in other industries : in other words, materials have a history, and in this history, they can flow in and then out of the "waste" category. Thus, few materials can be essentialised under a monolithic label of "waste". For instance, it is very significant that, in the [3] International Iron and Steel Institute (IISI, an industry body) study (IISI [3]), the only "wastes" studied in the global steel industry were BF and BOS slags, which are not particularly difficult, from a material point of view, to deal with, especially since they have many commercial applications. The point is reinforced by the fact that BF slag has was recently reclassified by the EU as a by-product, not a waste; this also shows the great inertia in attitudes towards what constitutes valuable materials or not. In the [4] IISI (IISI 1994) study, the list of wastes was much longer, and much more problematical. This study, however, still contained assertions that are unacceptable today, such as EAF dust being spread on fields as a "zinc supplement". This shows how fast the social, political and economic definitions of waste evolve, although they do not always necessarily intersect. More recent IISI studies take an even bolder and broader perspective, analysing the production of steel in a life-cycle perspective, i.e. taking into account all the environmental outcomes of the production of the metal. We thus have an example of a gradual broadening of (official) perspectives on waste in the steel industry.

Many of these by-products do not pose particular problems in terms of recirculation due to their material properties: they are carbon or iron rich for instance, with little or no undesirable substances, such as zinc or lead, and are not difficult and/or costly to collect and recirculate. Due to the unstable cost of raw materials, it makes sense to try and reduce coke consumption or losses of iron-bearing materials.

However, as we shall see below, for various reasons, not all materials can be reused: some materials are problematical, or, rather, have become so due to a conjunction of political and economic factors especially in the last 20 years or so. These problem wastes, and the symbolic, economic, environmental, political and social mechanisms and issues they reveal, are at the heart of this paper. We want to build an understanding of how these materials have been constructed as "problematical", in the technological, economic and social context of the contemporary steel industry, and its current mutations.

3 Methodology for analysing "problem" wastes

I now turn to the "problem wastes", and analyse the factors that make them such, i.e. their material, but also social, political and economic genesis. I also look at empirical material showing how these wastes are dealt with, practically and symbolically, by the industry, regulators and other industry experts ; in other terms, how the approach to these materials is co-produced by a variety of actors. The narrowing down of the vast array of by-products and wastes produced by the steel industry is based on interviews with steel company executives and steel industry consultants, as well as executives from global waste management companies working for the steel industry. Moreover, there is evidence in the literature documenting how problematical these wastes are (see IISI [4], for example).

One last point to have in mind before looking in detail at the "problem" wastes (or any waste produced by the steel industry for that matter) is the extreme variability in the quantities of waste produced, sometimes from 1 to 20 or more (IISI [3] and IISI [4]), according to the plant and the waste taken into consideration. This is due to several factors, including quality and type of raw materials, age and maintenance of plant, processes, as well as big differences in legislation (from country to country, but also historically in a given country), definition of materials, and in the adoption of new technologies and/or processes.

Moreover, the use of raw materials and the subsequent production of wastes are nonlinear processes (e.g. increased use of raw materials required in blast furnace when materials with high zinc content are used). That's why any understanding of waste in the steel industry will have to be place and time based to seize the historical and geographical differences: what is impossible in a given time and place may be standard practice at other times and places. However, based on the existing literature (Schultmann et al., [8]), and for the sake of clarity of analysis, we can assume that by-product generation is around 500 kg per tonne of steel in the global North, due to multiple pollution abatement apparatuses, which for instance transform emissions to the air into solid wastes by scrubbing etc. These wastes would therefore not exist without the latter devices but would simply be uncontrolled emissions.

(a) Blast furnace filter cake

The first "problem" waste we turn to is Blast Furnace Filter Cake (FC). FC results, ultimately, from the cleaning of BF off-gases (not the gases from tapping, which are captured in a baghouse and recycled to the sinter plant) by water-scrubbing. This sludge contains heavy metals (lead, zinc, cadmium, arsenic) and is very alkaline. Due to its high content in heavy metals and water, it is not readily recyclable through the production process (sinter plant then BF), notwithstanding its content in carbon and iron that makes it potentially re-usable. Zinc (Zn) in particular is a problem in the BF because it results in extra coke consumption and there is also a risk of scaffolding[4]: Zn evaporates because of the very high temperatures, then condenses on the walls of the furnace at lower temperature. The condensed Zn prevents the descent of the furnace load, which can lead to its sudden collapse, generating large amounts of dust and possible damage to the BF. Moreover, alkaline substances, such as sodium and potassium, can have

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[4] The maximum admissible Zn content per tonne of hot metal in the BF is estimated to be between 0.1 and 0.45 kg according to IISI [4]. More recent studies place it at an average of 120 g/t (0.12 kg).

negative repercussions on hot metal properties.

In the plants I studied, this waste stream used to be landfilled, but this is now impossible since a ban on liquids going to landfills, and also due to its heavy metal content: the material properties of the waste (both its chemical composition and its state, i.e. a liquid) therefore interfere, in the context of a changing regime of waste management, with its traditional fate, creating a botlleneck in the flow of materials from "cradle to grave". Of the several thousand tonnes produced every year, 60% was processed internally via the hydrocyclone process followed by the sinter plant, to reclaim Fe and C units. The remaining 40% was dewatered on plant by a contractor. Dewatering leaves a solid residue and a liquid one mainly constituted of water, which is left to settle in lagoons on the site, the water then being discharged via the wastewater plant. We thus see that the process of dealing with this substance has undergone increasing complexification, from "simple" dumping in holes, to separating streams. Things do not stop here, however, as the solid fraction cannot be disposed of to landfill, because it is officially classified as hazardous, due to its heavy metal content, but also to naturally-occurring radioactivity: FC contains Pb-210 and Pl-210 (isotopes of lead and polonium respectively), and therefore cannot be reused in the production process (BF and/or sinter plant) as this would concentrate radioactivity even more. A small fraction, via briquetting and blending with other by-products, can be reused in the BOS plant, plant operators are unwilling to increase this proportion due to cooling effects. Another issue is the fact that, according to a contractor in charge of a briquetting plant, the FC was not being sufficiently dewatered by the contractor in charge of the latter, meaning that more processing had to take place before the FC could actually be briquetted. Most of the FC was thus stockpiled on plant. This stockpiling was a growing problem, especially at another plant where there were significant legacy piles due to the absence of landfill availability. Some executives of the plant saw a solution to these stockpiles in the Rotary Hearth Furnace process which volatilises the Zn and Pb contained in BF filter cake, leaving the iron oxide, whilst concentrated Zn and Pb units can be recovered and then sold. However more senior plant managers were not interested in pursuing this avenue, opting for other outlets, such as using blast furnace filter cake in the cement industry.

In this case, we see that it is the change in legislation that, initially, made the waste a "problem", because it just used to be dumped before, without any "problems" for anyone : the material just did not really appear on anyone's radar. It was not even the same waste in a certain way, as the dewatering of the sludge creates two streams of waste, one solid and one liquid, where there used to be a single (liquid) one. The necessity to deal differently with a substance that used to be "simply" landfilled fully reveals the problematical material properties of the filter cake, i.e. its high content in unwanted substances, that seem to be revealed by the necessity to dewater it (as a plant executive puts it, "we used to have a non-hazardous fluid, now we have two hazardous waste streams"). The steel production process, in its present state, cannot cope with this added source of Zn, but not only for material reasons: there is a reticence to reorganise production to accommodate this material (in the BOS plant, where it would not pose so much of a material problem, but an organisational one, due to a cooling effect, instead of the BF), and the industry are therefore stuck with a growing stockpile of the "stuff".

(b) Oily millscale sludge

The second problem waste was oily millscale sludge. Rolling steel requires the use of oil (to lubricate) and water (as a coolant); the two combine with millscale to form a sludge from the oxidation of steel; most of this millscale is not contaminated with oil and can be readily recycled to the sinter plant due to its high FeO_x (iron oxide) content. Several thousand tonnes of the oily type were produced every year at one of the steel plants I studied. The sinter plant could not take this material, although it is rich in iron oxide, because the presence of oil would have caused a potential fire hazard, on the one hand, and, on the other hand, emissions from the sinter plant would have been in breach of opacity standards. Various experiments were carried out to remove the oil, such as bio-remediation (also attempted in the USA), or the construction of a dedicated solution at another plant, for £3 m. The material was also being dewatered, and the solid fraction was landfilled. According to an executive, "no one has a real solution to this, we're just making it into a non-liquid" to be able to landfill it. Here again, legislation combined with the material properties of the substance to create a "problem waste", although, in this case, the flexibility of the definition of a "waste" (and even more so of a "hazardous waste") was illustrated by the fact that this substance had gone from hazardous to non hazardous, once again emphasising the fact that the same materials can travel through several conceptual categories based on the capacity of the industry to negotiate with regulators.

(c) Electro-static precipitator dust

The third "problem" waste was Electro-Static precipitator (ESP) dust, from the sinter plant (there is also an ESP at the steelplant, but it did not produce any problem wastes). The ESP is the most commonly used dust abatement technique. However, the composition of sinter plant dust hinders the optimal operation of the ESP: the dust contains heavy metals, is alkaline and radioactive[5]. Part of it is reused in the briquetting plant ,but the contractor are now saying that they have too much ESP dust in their mix and so cannot take it all. Part of it can also be re-used in the sinter plant itself (the sinter plant is one of the main routes for the recycling of reverts in the steel industry, with up to 85% of all in-plant recycling[6]), however there is a limit to how much the sinter plant can take, as it was not designed first and foremost to be a waste disposal route, but part of an integrated steelmaking process. This dust is hazardous due to its composition of course, but also its consistency which makes it difficult and dangerous to deal with: it is very fine and very dry dust and handling it would require very qualified personnel; also, any kind of dust (especially fine) needs to be agglomerated before it can be used in any process, adding to the complexity and cost of dealing with waste. This dust is currently being stored.

(d) Lead-containing waste

Lead-containing steel is used by the automobile industry for its machineability. A lot of the lead is lost in the production process: one third is contained in the fumes released during production. These fumes are treated via bag filters, which collect high-lead dust (60–70% lead content, 20% of the dust) and low-lead dust (around 10% lead content, 80% of the dust). Around 200 tonnes of dust are produced per year at the plant studied. This dust is difficult to deal with, firstly because, obviously, it is highly toxic, and also because it is very dry and will not readily dissolve to form a sludge when treated with water; instead, it forms little balls that can explode at any time and release the hazardous dust, making it hard to handle (versus dewatering BF cake for instance, which is standard practice). The low-lead dust used to be landfilled on site, but this was now prohibited, and hazardous wastes landfill sites were deemed "too expensive". The high-lead dust used to be sent to smelters, which have now closed, so the dust was being shipped "to the Far East" as this is cheaper than landfilling;. Here, we see that a combination of legal and economic factors contribute to placing the lead-containing waste in an international political economy of waste, as it is cheaper to ship "to the Far East" than landfill it in specialised landfills in higher cost countries. Moreover, the domestic industry that used to handle this waste had shut down, illustrating the reliance on international circuits. Another aspect of the question is that, in practical terms, more lead-containing dust could be recycled on plant, but this would imply some organisational changes. The company, following industry-wide practice, chose to concentrate on its "core job" in an effort to

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[5] The radioactivity of sinter plant emissions was first identified in the Netherlands, and derives from the presence of trace amounts of uranium and thorium, and their decay products in the iron ores and coals used for ironmaking. The main isotopes emitted during sintering are lead-210 and polonium-210, which become concentrated in the waste gas.

[6] IISI seminar on sinter & pellets [5].

cut costs, which can be witnessed in the use of contractors for more and more operations, and the subdivision of activities among several contractors to drive prices down.

(e) Dust from electric arc furnaces (EAF)

This is generated during the production of steel in EAF plants. Several thousand tonnes were produced every year by certain plants. The dust is captured in filters in baghouses. The problem with this dust, once again, is its Zn content. It could be landfilled until a few years ago, when this practice was banned. Attempts to use this dust in the briquetting plant after concentration had proven uneconomical: Zinc smelters consistently try to get a higher zinc content while demanding to pay less, or even to be paid, to take the dust. So this dust was being shipped abroad, to be used in the production of cement, failry standard practice in the industry (IISI [3] and IISI [4]). Once again, we see the international circuits of waste, and how they can be mobilised by steel companies to, in a way, evade costly domestic regulations, and also deal with materials for which there is no infrastructure in the country of origin.

4 Conclusions

Many factors preclude the optimal reuse of various by-products arising during the production of steel. These by-products become wastes, materials with no obvious applications, and they are also a liability. They all require relatively costly and time-consuming pretreatment to be reused in the integrated processes, and/or contain unwanted substances such as zinc and other heavy metals that can hinder the process and affect product quality. Also, the physical characteristics of the wastes (oily sludge or very fine-grained material) can preclude their reuse. All in all, this illustrates the fact that the components of the steel plant are designed primarily to produce steel, and not to recycle wastes: there are limits to how much of these wastes they can handle, and only materials containaing desirable substances (FeOx, C, fluxes) are readily recyclable. This makes the idea of separate waste processing routes[7], such as rotary hearth furnance processes or variants thereof, potentially appealing, though this can be seen as non-core business.

However, more than the availability and cost of technology, problems surrounding these materials also come down to organisational issues, such as the resistance to using more briquettes, or the selection of inadapted processes by contractors who are often asked to manage more and more by-products at an ever lower cost. Furthermore, recyclates are not necessarily reused. Indeed, one of the plants investigated wasn't actually using its briquettes, due to their higher cooling effect when compared to scrap, although they are cheaper. Thus, the briquettes were just piling up, posing the question of whether there is any real commitment to reusing the materials in question, and at any rate leading to the loss of recoverable materials. The company prefered to pay third parties to take these materials and ship them abroad, and recover the values themselves, than modify some of its processes to accommodate these materials.

It is thus clear that social sciences have something to say, as all is not down to technology, but also to the way it is integrated (or not) into organisational routines, on the one hand, and what the strategies behind the use of these technologies are, on the other. Likewise, issues of knowledge building, codification and transfer between companies or even divisions of a given company, and between companies and contractors, are also socially constructed. Therefore, the steel industry can be taken as an exemplar of the necessity for social sciences and industry to collaborate more often and on a wider array of topics.

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[7] As well as the insertion of wastes in international circuits, as already noted before.

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