

Embedded industrial production systems Lessons from waste management in zinc production

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Abstract

To meet the sustainability challenge private companies must implement corporate strategies and adopt novel technologies. The technical and social embeddedness of industrial production systems, however, complicates these systems' transition towards sustainability. In the paper, mechanisms and conditions are reported for the development and implementation of waste management options in embedded industrial production systems. The focus is on the Dutch zinc production industry, which had to deal with a major waste problem; the generation of jarosite. The industry's options were to increase the jarosite waste storage capacity, to develop a jarosite treatment process or to switch to a zinc-ore of low-iron content whereby no jarosite waste would be generated anymore. Required conditions appeared to be a combination of technological capability and technical embedding and favourable economics. Case study research, however, revealed that adequate stakeholder management is crucial to address social pressure exerted and to obtain external acceptance for any transition strategy. Whilst appropriate, internal technological capabilities are important, effective interactions with and enrolment of various firm-external actors are crucial. In the case of zinc, access to the heterogeneous external actor network was critical for the development of the jarosite treatment solution direction. In conclusion, both the technical, organizational and social embedding of new technologies are crucial for successful implementation.

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1. Introduction

Humanity presently faces a major societal and environmental challenge to achieve the right balance between consumption, production, prosperity and population growth and Earth's carrying capacity. Drastic change in both consumption and production systems are required in order to meet the growing needs of a growing population while using the Earth's resources in a sustainable way.

This paper focuses on industrial production activities, which play an important role in resource consumption and have a history of being an important source of environmental pollution. More importantly, however, industrial activities represent potential nuclei for technological development for the closure of material cycles [1].

It is well known that a great many technological innovations never make it to the market. In most OECD countries, however, R&D activities both in industrial and public research centers are substantial. It may thus be seen that there must be a great many technological innovations that are 'waiting in the wings' to become commercially attractive, many of which have even already been tested beyond the laboratory in small, pilot scale operations. Apparently it is difficult to implement such technological innovations.

We conjecture that the embedment of present industrial production systems presents an important barrier for technology diffusion to the market. Embedded industrial systems exhibit large scale of operations, a high degree of technical complexity and social intertwinement. These characteristics represent phenomenal barriers to change in established production systems, which includes adaptation to as well as adoption of new technologies while past investments (sunk costs) must be recovered.

In order to elucidate how such embedded industrial production systems can meet the sustainability challenge, the focus of this paper is on the conditions that influence the development and implementation of more sustainable technologies in primary metals production. We use the Dutch production of primary zinc as an example of an embedded production system that must deal with a major waste problem, i.e. the generation of jarosite.

Firstly, embedded industrial production systems and sustainability are briefly addressed. Secondly, the Dutch zinc production system is described and the various technological options available for waste management are summarized.² Third, the conditions that influence the development and implementation of solutions are analyzed. Finally, the results are discussed and conclusions drawn.

2. Embedded industrial production systems and the sustainability challenge

Industry and consumer products impact the natural resource base via the entire cycle from raw materials exploration and extraction to the final use and disposal of products by consumers. Each transformation of resources into product is associated with some energy use, emissions, and the generation of waste. The associated impacts may be positive because the quality of a resource base is

² The empirical part of this paper builds on [9], pp. 113–147.

enhanced or its use is extended. Presently, however, negative impacts appear to prevail, as both production processes and products cause environmental pollution and contribute to the depletion or degradation of resources. Energy use fuelled by fossil resources threatens to severely impact our global climate through the associated CO₂ emissions.

Industrial production activities therefore cannot be considered in isolation. In industrial ecology, indeed an integral approach is advocated as well as the closing of materials production and consumption chains [2]. Whilst the resulting closed industrial systems do require the use of energy and the input of some natural resources while generating waste, these are expected to be at much lower levels than open industrial production systems [3]. Many industrial corporations and sectors already have been making considerable efforts to limit their environmental impact by means of technological innovations, both in the area of their production processes, and in the use, disposal, and recycling of their products. In industrial parks the waste from an industrial process can be rerouted back to the same process or it may serve as the raw material for another process in the park, thereby reducing the total environmental impact. In the steel production and consumption cycle, for example, techniques for recycling are well established, and there is a strong infrastructure for collecting scrap [3].

Other industrial activities, however, still result in considerable environmental impact. The product intensity of some industrial sectors largely contributes to unsustainability. The production of pharmaceuticals, for example, causes a great deal of pollution per unit of product. Fortunately, the production volume of most pharmaceuticals is small. In contrast, bulk chemicals are produced in large quantities. The scale of a particular industrial sector contributes to a large extent to its environmental pollution. In the taxonomy of Pavitt [4] the studied zinc industry must be labeled *scale-intensive*, its scale of operations being large, its product zinc slab rather undifferentiated. The pulp and paper industry, the bulk chemicals industry, the printing industry, and the automobile industry are also examples of such scale-intensive industries.

In addition, the *nature* of the raw materials must be accounted for. Many raw materials are composed of inherent ‘waste’ materials in addition to the exploitable valuable materials.³ These have been labeled ‘Verlustrohstoffe’, as opposed to the ‘Reinrohstoffe’ that are clean in itself, such as natural gas [6].

A number of options are available to improve sustainability of industrial production systems such as:

- Organization and management: optimization of environmental performance by good housekeeping, introduction of environmental management and total quality management systems,
- Technological change and innovation: the use of appropriate end-of-pipe techniques, the application of cleaner production processes based on innovative clean technologies developed and integrated in process system (re)design,
- The closure of material cycles and system improvement [2,7]: reduce the loss of materials discarded as waste through the connection of primary production, consumption and waste management subsystems in society through product re-design, production system reconfiguration and recycling infrastructure development.

³ For example, only 53% of the zinc concentrate consists of the element zinc, the remainder being sulphur (32%), iron (7.3%), lead (1.6%), titanium (1.2%), silicon (0.81%), copper (0.59%), calcium (0.42%), manganese (0.36%), cadmium (0.24%), magnesium (0.19%), arsenic (0.14%), mercury (0.0011%) etc. [5].

Public policy for sustainability, for example a ban on the use of environmentally unfriendly, must be devised and implemented to provide sufficient economic incentives. In addition, the embeddedness of present industrial production systems has to be taken into account.

2.1. Technological change in embedded industrial production systems

The fundamental renewal of production processes in embedded industrial production systems is not an often observed phenomenon. This can be understood by looking at the underlying drivers and barriers of technology development.

1. *Economics and risk*: New technology often requires high investments, and radical new technologies entail high financial risks. In addition, there are risks related to safety, health and the environment associated with the use of as yet unproven technology that may evolve into financial claims.

Another barrier to implementing radical new technologies in scale-intensive industries is the capital-intensity of its large production installations. Whilst the capital invested usually is recovered during a depreciation period of some 15–20 years, their technical life span may be as long as 30 to 50 years. Since the commodities produced also have a long economic life span, (these basic products are expected to be necessary in 40 years time), it is attractive to continue production in 20 years and installations for which the initial capital has been fully recovered.

2. *Embeddedness*: New technology must be integrated into broader technical, economic, social systems and networks of actors and meet various specifications:

a) Specific qualities for matching

For example, a new or additional step in a production process must physically fit into the established production system and, in addition, new technologies require different types of training, learning, and regulatory legislation.

b) Generic qualities enabling matching at the same time, satisfy many qualitative requirements (performance, user-friendliness, etc.)

As a consequence, when economics or requirements for embedding a new technology are lacking, the spread of a new technology can be expected to proceed only slowly. Accordingly, manufacturers tend to favor the development that can be incorporated into an existing production process with only modest changes in the organization of production: of add-on or end-of-pipe technologies as well as improvement of existing production processes. Thus, especially in the short term, strategies of adopting incremental innovation predominate over strategies that require breakthrough technologies and a total reorientation away from established production systems.

Since scale-intensive, embedded industries are predominantly positioned at the beginning of many production chains, changes in scale-intensive processes can have a serious impact on the sustainability of these production chains.

3. *Continuous improvement*: In scale-intensive sectors, established producers benefit from the dynamic effects associated with its scale of operation and from learning-by-doing. This can be translated into price reductions, scale advantages and better production performance. According to Stobaugh [8], for such industries and sectors these are the major factors firms compete by. Beyond the level of a single plant, the intertwining of the large-scale production systems complicates the implementation of radical new technologies. This intertwining includes the diversity and logic order of processes.

4. *Character of materials*: Metals production uses various additives or auxiliary materials, and the production process depends on specific raw materials that, upon processing, inevitably yield waste materials [9].

3. Zinc production and waste management

3.1. Characteristics of the zinc production industry

The zinc production industry includes a highly intertwined production infrastructure, and is a resource- and energy-intensive industry. It is environmentally sensitive, due to its scale-intensity, its production processes and due to the nature of its raw materials, i.e. ‘Verlustrohstoffe’ [6]. In the sector the focus is on the most efficient production. There is relatively little product innovation, but relatively intense process innovation focused on producing existing products at lower costs. The zinc products have the character of standardized commodities that function as intermediate goods in a large number of applications. Competitiveness is determined by price, and, therefore, by cost leadership in industrial production.

The flows of zinc in society encompass zinc-ore mining, primary zinc production, semi-fabrication of zinc, industrial as well as consumer use of zinc, zinc recycling and secondary processing, and zinc waste. The zinc production and consumption chain is summarized in Fig. 1. It is physically intertwined and socially embedded in various parts of society through, amongst others, cars, gutters, and batteries [9].

The most common process to produce zinc is the hydrometallurgical roast–leach–electrowinning process that uses sulphidic zinc-ore that contains ZnS. The process consists of five basic steps: concentration of the zinc content, roasting of the zinc concentrate ($\text{ZnS} \rightarrow \text{ZnO}$), leaching of the zinc oxide ZnO, purification of the leach liquor, and electrolytic recovery of zinc. To achieve a reasonable recovery of zinc, a significant amount of iron is leached along with the zinc that must be removed from the solution to produce a marketable zinc product. The most common approach is to precipitate the iron using an alkali, such as sodium, potassium, or ammonia, and produce the insoluble jarosite.⁴ Because of the heavy metals present in the jarosite matrix and the risk of heavy metal leaching, controlled jarosite-storage is mandatory. Despite the high iron content, the jarosite cannot be co-processed in steel plants because of the zinc present in the material. The amounts produced are large: around 1 ton of jarosite is formed per 2 tons of zinc produced. A zinc plant also generates gypsum (CaSO_4) as a co-product. Other

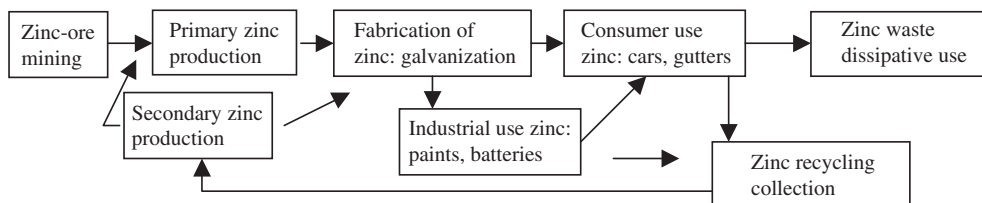


Fig. 1. Zinc production and consumption chain.

⁴ The jarosite process produces $\text{MeFe}_3(\text{SO}_4)_2(\text{OH})_6$ ($\text{Me} = \text{K}^+, \text{NH}_4^+, \text{H}^+$). This iron-containing precipitate could also include small amounts of lead, arsenic, cadmium and mercury.

major byproducts recovered at zinc plants are sulphuric acid, cadmium metal, silver/lead products and copper- and cobalt-enriched products. Emissions from zinc plants are metal-containing flue gas, as well as sulphur dioxide from the sulphuric acid production [5,9,10]. Fig. 2 presents the hydrometallurgical zinc production process.

Zinc is an important metal that finds wide application in society. Today, zinc is the fourth industrial metal produced by volume and surpassed only by steel, aluminium and copper. More than 50% of the zinc metal produced is used as an anti-corrosion protector on cars [10,11]. Thus, it may be seen that both in processing and the subsequent product chains the zinc production system is interwoven with the steel production system. While the zinc production delivers an iron-bearing waste stream that in principle could be used as input in the steel industry, the secondary steel industry delivers zinc-oxide-containing waste, which could be reprocessed in the zinc industry.

3.2. Zinc production and the sustainability challenge

In spite of many innovative efforts, the zinc production industry is still inducing some serious environmental problems. Each ton of consumed zinc involves many tons of ores that have to be mined, purified, and processed. As a matter of fact, many of the environmental problems induced by zinc production are due to its dependence on ‘Verlustrohstoffe’. Zinc is extracted from mineral ore bodies (mainly sphalerite), which also inherently include traces of other elements. Many of these elements could often not be efficiently processed and end up in the jarosite waste stream of the primary zinc production process.

Accordingly, the most important environmental problems of the zinc production industry include:

- The production of large amounts of jarosite waste;
- Emission of sulphur dioxide after sulphuric acid production;

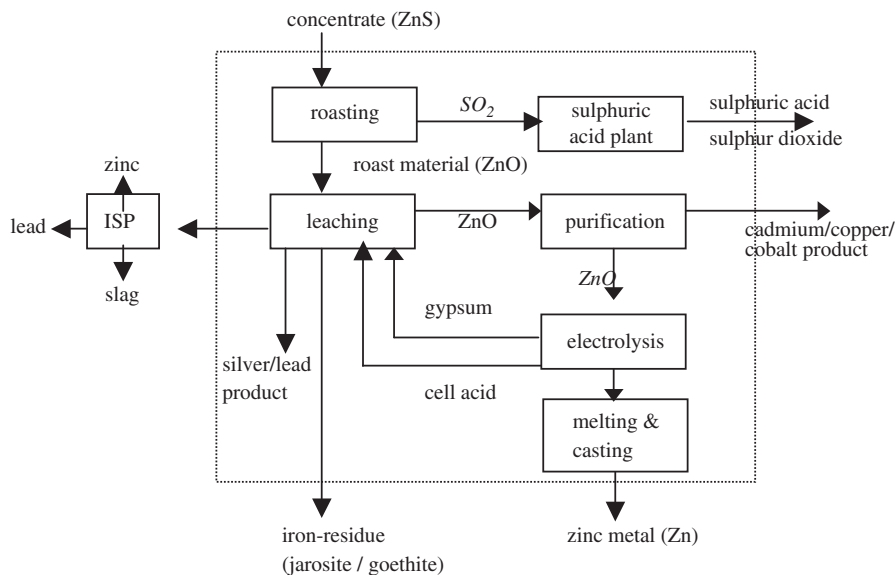


Fig. 2. Hydrometallurgical zinc production process.

- High energy consumption of the primary zinc production process⁵ and the associated carbon dioxide emissions;
- Dissipative use of zinc as an anti-corrosive agent. Whilst zinc recycling from new and old scrap from galvanizing, brass and die-casting is high, significant loss of zinc to the environment occurs. In addition, zinc is often used in a form, which makes it difficult or expensive to recover, due to the fact that zinc metal is applied in very low concentrations in some products. Annema et al. estimated the yearly dissipative zinc losses in the Netherlands to be around 8700 tons, of which circa 4000 tons come from corrosion [12].

The jarosite waste is the major environmental problem of the zinc production industry. In the future, the willingness to accept the disposal of large amounts of waste may gradually disappear in many countries.⁶ The realization that jarosite waste ponds will no longer be accepted as a way to solve the zinc producers' waste problem has stimulated research on alternative waste handling methods.

3.3. Dutch zinc production and waste handling options

The Netherlands has one primary zinc production plant, Budelco, which is situated in Budel-Dorplein in the southeastern part of the Netherlands. As of 1995, Budelco is a wholly owned subsidiary of the Australian company Pasminco⁷ and the firm is known as Budel Zink since. It is one of the larger zinc production plants in the world, with an annual production capacity of more than 200,000 tons of zinc, which represents $\pm 4\%$ of world zinc production. Budel Zink produces zinc by the hydrometallurgical roast–leach–electrowinning process and is a principal supplier of Special High-Grade Zinc (99.995%) and specific zinc alloys to the steel industry in the Netherlands, Belgium, Germany, France and Austria. It also produces some important byproducts such as sulphuric acid, cadmium metal and copper- and cobalt-enriched residues. Since 1973, jarosite has been produced at Budelco, now Budel Zink. The jarosite waste stream has been disposed off in four isolated tailing ponds that have accepted some 120,000 tons jarosite waste per annum. The gypsum formed during production has also been stored in ponds.

Under the growing environmental consciousness of the 1970s, environmental and societal groups in the Netherlands increasingly protested against the rising environmental pollution by industrial activities. When in the 1980s studies [14,15] demonstrated a large cadmium pollution of the gardens in and around Budel-Dorplein, which represented a direct danger to the food chain, the societal pressure on the zinc production activities grew enormously. Budelco became the scapegoat, while in fact, this cadmium and zinc pollution of the soil was mainly an inheritance of the pyrometallurgical zinc production as it existed before 1973.⁸ This cadmium-pollution study was the main incentive for local, provincial, and national authorities to impose a more severe environmental regulation on Budelco and to pay closer attention to the environmental problems related to its current zinc production.

⁵ Primary zinc production consumes about 15 GJ/ton of zinc. Electrolysis uses about 80% of that amount [13].

⁶ In several countries, zinc refineries are now already facing a deadline for pond disposal of leach residues. In the Netherlands, such a deadline has already been set, demanding alternative ways of jarosite waste management in the zinc production industry.

⁷ Pasminco is one of the world's largest integrated zinc and lead producers, supplying approximately 7% and 4%, respectively of the global demand for finished zinc and lead metal [9], p. 125.

⁸ This historical pollution has been built up during more than 100 years of pyrometallurgical zinc production activities in the Dutch and Belgium Kempen.

At the time, three solution directions for managing the jarosite waste problem at Budelco: increasing the storage capacity of jarosite waste by building new tailing ponds, treatment of the jarosite waste, and input of low-iron containing zinc concentrate in the primary zinc production process, were producing no jarosite waste at all.

3.4. Increased jarosite waste storage capacity

Under the growing societal and environmental pressure of the early 1980s Budelco was forced by the provincial and national authorities to find a more definitive solution to the jarosite residue than depositing the waste in tailing ponds.

In 1982 Budelco started their research on the processing of jarosite waste into an environmentally acceptable product at laboratory scale. In 1984, when Budelco announced that the first jarosite pond was leaking to the underground, contributing to groundwater contamination, the local environmental movements, political parties and neighboring communities put increasing pressure on the company to tackle its jarosite waste problem. A license request made by Budelco for the building of an additional third jarosite tailing pond⁹ gave rise to opposition from environmental groups, such as Stichting Natuur and Milieu¹⁰ and the Brabantse Milieu Federatie [16].¹¹ In the same year, Budelco presented a jarosite notice in which two alternative processes seemed to have the best perspectives: application of the hematite leaching process, or treatment of jarosite with sulphuric acid [17].

Meanwhile, the company director of Budelco kept asking provincial and national authorities for more time to develop a process for the treatment of jarosite. The company even threatened to shut down the entire zinc plant in case it had to meet the severe environmental restrictions. Their strong argument was that a closure of Budelco's zinc plant would give rise to a high local unemployment in the southeastern part of the Netherlands. In 1985, the Province gave Budelco respite for the development of a jarosite treatment process and a 10 year temporary license to build a third jarosite tailing pond to store the jarosite waste, provided that they would try to find a final solution to the jarosite problem. Environmental groups appealed against this decision [18]. In 1986 Budelco presented an environmental notice in which the so-called 'Oxysmelt' process¹² seemed to be the best alternative to treat the jarosite waste, at the expense, however, of significant investments and high energy use. Additionally, they further studied the hematite leaching alternative on a small scale.

3.5. Jarosite treatment process

In 1987, the Province of Noord-Brabant formed the 'Steering Group Budelco' (in Dutch: Stuurgroep Budelco), a technical working group at national level studying the jarosite treatment process in order to find solutions to the jarosite problem. The following parties participated in this Steering Group: Budelco,

⁹ At that time the second jarosite waste tailing pond was running out of capacity. A new pond was necessary to continue zinc production, because every ton of zinc produced delivers about 0.6 t of jarosite.

¹⁰ The 'Stichting Natuur & Milieu' is a Dutch foundation that specifically looks after the general interests of nature and the environment.

¹¹ The 'Brabantse Milieu Federatie' is an independent provincial federation looking after specific environmental interests in the province of Noord-Brabant in the Netherlands.

¹² The Oxysmelt process is a pyrometallurgical cyclone smelting process in which the jarosite is pyrometallurgically treated at high temperatures, and a residue is obtained in the form of a slag.

the environmental officials of the provinces of Noord-Brabant and Limburg, officials of the Ministries of Economic Affairs, of Environmental Affairs, and of Social Affairs and Employment, and technical advisors of Delft University of Technology and the Dutch technical research institute TNO. This Steering Group recommended the treatment of both the jarosite already present in the tailing ponds and of the structural release of new jarosite during zinc production [17]. In the period 1989 to 1991 various research projects worked on the treatment of the slag of the Oxysmelt process with the aim of finding an application for it [19]. TNO concluded that the leaching behavior of this slag was favorable.

In addition to the Steering Group, Budelco was participating in the ‘Jarosite Working Group’, set up by the Canadian zinc company Noranda Valleyfield and consisting of members of six zinc (and jarosite) producing companies¹³, with the goal of combining efforts on a global scale in managing the jarosite waste problem by developing jarosite treatment options. After all, a lot of know-how about waste treatment and emission control was developed within the zinc companies itself. For a long time it remained uncertain whether the Oxysmelt jarosite treatment process was technologically feasible. In 1992, large scale smelt and duration experiments with jarosite and other waste materials were run at the Research Center of Finnish metals producing firm Outokumpu, being a specialist in pyrometallurgical processes. In fact, the jarosite treatment process had been partly based on principles of Outokumpu’s successful flash smelting technology for copper. The conclusion of these tests was that the jarosite slag obtained was very compact with a relatively low content of heavy metals. The slag could be stored safely or presumably be applied as foundation or construction material in road building or in the cement/steel industry.

In the early 1990s, the jarosite treatment process turned out to be technologically feasible, but too expensive, due to its high energy use and operating costs.¹⁴ The national government didn’t want to co-finance the treatment process,¹⁵ and the company was not willing to pay the costs of building and operating the jarosite treatment process alone. Applying the jarosite treatment process would give rise to additional operational costs for Budelco, so it would be attractive if the energy need of the process could be gained from processing other waste streams.

At that time it seemed to be possible to process jarosite together with other waste streams, such as waste oil, zinc ashes, gypsum and polluted sludge. Such a combination was called the ‘co-treatment option’, in which the sludge or waste oil could serve as the caloric need in the process, lowering the operating costs of the treatment process. Both the jarosite problem and the large amounts of waste oil and sludge would have been solved in applying just one treatment process. A separate working group was formed around the co-treatment option, including members of the provincial authorities, the Water Boards and the technical institute TNO.

In the period 1991–1992, various research projects were performed with several waste materials that would in principle be appropriate for treatment together with jarosite in the Oxysmelt process. In 1992, smelting experiments with the co-treatment process (including sludge) were again successfully performed at Outokumpu [18]. In addition, the engineering bureau Tebodin did some studies to find out to what extent the processing of wastewater sludge put forward by the provinces of Limburg and

¹³ Worldwide Budelco, Nordenham, Det Norske Zinkkompani, Outokumpu Kokkola Zink, Asturiana and Noranda Valleyfield were involved in the Jarosite Working Group.

¹⁴ During the research period the estimated costs for jarosite treatment went up from 300 to 900 million guilders: a rise from about 150 to 450 million (USD).

¹⁵ The government didn’t want to establish a precedent financing the jarosite treatment process.

Noord-Brabant could be integrated with the jarosite treatment process. They studied the investment costs of separate and joint integrated treatment of jarosite and concluded that joint treatment provides financial advantage for all parties. Accordingly, co-treatment of other waste made the jarosite treatment process economically favorable.

Despite the conclusion of the Tebodin report, co-treatment didn't appear to be achievable in 1992. The willingness of the various parties was lacking. The Water Boards¹⁶ of Noord-Brabant and Limburg were developing their own sludge combustion processes. Furthermore, the input of waste oil in the co-treatment process was undesirable from the viewpoint of the national environmental policy, because a political decision about a higher-grade treatment of waste oil was on the verge of being reached. A new waste oil combustion oven was already planned for construction by the company Texaco. Accordingly, the provincial and national authorities and the regional Water Boards didn't want to give up their interests and control over building their own treatment plants for waste streams, such as oil and sludge. In addition, there was no agreement in the working groups as to which would be the better technology for jarosite (co-)treatment. Hence, the co-treatment option was canceled and finally the jarosite treatment process was not implemented. The jarosite treatment process was not economically viable and far more expensive than controlled disposal in tailing ponds.¹⁷

By the end of 1993, the jarosite treatment option was definitively canceled, and Budelco had reached a framework agreement with the Dutch authorities regarding definitive storage of jarosite and gypsum, with the regulatory claim in the license that Budelco was no longer allowed to build new jarosite ponds and that its disposal of jarosite in ponds would be ceased from 1 July 1998. Thus, Budelco had to find a new zinc production method without jarosite formation.

In addition, Budelco had to take protective measurements for the existing ponds. Budelco's long-term environmental program, as agreed with the national authorities in 1993, principally involved the sealing and capping of the four jarosite ponds and two gypsum ponds to ensure that they remained environmentally benign into the future.¹⁸ Budelco also agreed to clean up the historic waste residues of zinc ash, which had been stored on-site.¹⁹

3.6. The input of low-iron zinc sulphide concentrates in the production process

In January 1993 Budelco presented in the Steering Group another solution for the jarosite waste problem: the use of 'clean' low-iron zinc sulphide concentrates in the zinc production process, which wouldn't produce any jarosite at all. Instead, a lead-containing byproduct was formed. This new type of zinc concentrate was discovered in the Century mine in Queensland, Australia. One of the unique features of the Century deposit was the very pure nature of the zinc mineral sphalerite, containing an average of 60% zinc and less than 1% iron and manganese.²⁰ The mining company CRA came across

¹⁶ Water Boards ('Waterschappen') are the Dutch authorities that control the water quality and operate water treatment facilities, including wastewater treatment plants.

¹⁷ Budelco would no longer be able to compete with other zinc companies if they had to pay the investment costs and the yearly operating costs (~17 million USD) of jarosite treatment themselves [18].

¹⁸ The four jarosite ponds are wrapped up as four parcels, being covered by sand bentonite and plastic. The bottoms of the ponds have drainage systems for pumping the liquid from the jarosite mud. In the end, a thick paste will remain completely sealed in plastic and bentonite.

¹⁹ The jarosite and gypsum ponds require rehabilitation and long-term maintenance to prevent erosion of the walls and ingress of water and leaching of the stored residues into the groundwater. Three jarosite ponds and one gypsum pond are capped by December 1999. The remaining ponds are still in use and will be capped when jarosite/gypsum production ceases (mid 2000).

²⁰ Sphalerite from other deposits contains $\pm 10\%$ iron and manganese and about 55% zinc [20].

this low-iron containing ore lode, and Budelco pounced on it, being 50% owned by Pasminco at that time.²¹ The mine contained about 10 M tons of low-iron zinc sulphides and, with a minimum life span of 20 years, is one of the largest zinc mines of the world.²²

The planning was that Budelco would be producing zinc with the input of this low-iron zinc concentrate in 1998. The prerequisites were that Budelco got the guarantee from the Dutch authorities for permanent storage of historical and new jarosite which was still to be produced until 1998, that a proof of realization took place of the clean-ore mine option, and that a joint venture was formed between Pasminco/CRA and Budelco. As early as 1993, various meetings were taking place between the Dutch national and provincial authorities, Budelco, Pasminco and the Australian authorities on the realization of the ‘clean-ore’ route. The regional authorities in Australia were involved in granting the licenses for exploitation of the Century mine containing low-iron zinc-ore. The Dutch Authorities required that Budelco give a decisive answer in 1995 about the technological and economical viability of the application of the low-iron zinc sulphide concentrates in their zinc production process. Next, the authorities wanted a guaranteed takeoff of the lead-containing residues of this new process. The residues had to be applied as an acceptable secondary raw material for lead smelters.

There had, however, been unexpected problems associated with the exploitation of the Century mine. More than 5000 Aboriginals, living in an area of 300 km around the mine, were blocking the mining project. They didn’t want to sacrifice their territory and hunting areas for a large-scale mining project, in which a 300-km long pipe had to be buried through their traditional ‘holy’ territory through which the zinc concentrate had to be transported to a new harbor. Accordingly, the “right to negotiate” process under Australia’s Native Title Act delayed the commissioning date for the Century mine. Consequently, the Aboriginals’ protests delayed the delivery of low-iron zinc concentrate and the adaptation of Budelco’s zinc production process to the new type of zinc-ore. For a long time it remained uncertain then whether the mining project would definitively proceed. In 1997, The Dutch authorities agreed to extend the license for jarosite in ponds until 1 July 2000, giving Budelco an additional two years to deposit jarosite waste. This was necessary to bridge the gap between the start of the new low-iron zinc production process, and the stage of development of the Century mine.

In 1997 Pasminco purchased the Century deposit from CRA. The mine would produce about 500,000 tons of zinc concentrates annually, half of which will go to supply Budelco, making Budelco the main customer of low-iron zinc concentrates.²³ In May 1997, the Gulf Communities Agreement reached between Century Zinc, the local Aboriginal communities, and the Queensland Government was registered with the Native Title Tribunal, about the exploitation of low-iron sulphide deposits as feed for Budelco.²⁴ This cleared the way for leases to be processed and for the supply of low-iron zinc sulphide concentrates for Budelco.

²¹ Before the discovery of the Century mine Pasminco had been partly owned by CRA. In 1995 CRA disposed of its remaining 10% shareholding in Pasminco, because CRA only wanted to focus on mining activities. However, the Director of CRA kept chairman of the board of management of Pasminco [18].

²² With the takeover of the Century Mine, Pasminco became one of largest zinc concentrate suppliers of the world and the largest integrated zinc/lead smelter of the world.

²³ The mine was commissioned in late 1999, with the mine reaching full production during 2001, and the first low-iron concentrates arriving at Budel in early 2000, thereby allowing the production of jarosite waste to cease [21].

²⁴ Pasminco honored the Native Title Agreement negotiated by Century Zinc and the Aboriginals, which provided large economic and social benefits to the Aboriginal communities. Pasminco paid about 48 million (USD) to the Aboriginals for infrastructure and education. Also 200 Aboriginals could be employed in ore winning [22].

In the meantime, Budelco was already buying zinc concentrates with lower iron percentages to produce less jarosite. This was done to prevent the fourth jarosite pond from filling up before the implementation of the new zinc production process. Due to pressure from the provincial authorities, Budelco was not allowed to enlarge its jarosite deposit capacity with a fifth tailing pond if the supply of low-iron zinc concentrate was retarded. Otherwise they had to shut down their plant until the new concentrate was actually available [18].

Budelco's existing zinc production process had to be modified to allow the feed to be 100% low-iron zinc concentrates. Adaptations of the roasting process step and process parameters were necessary because the new zinc concentrate comprised other elements than the zinc sulphide ore normally used. In addition, the leaching process step needed to be transformed. The iron precipitation step had to be removed and adaptations had to be made for the winning of a lead/silver byproduct. The iron residue from the treatment of the low-iron zinc concentrates, Budel Leach Product, would contain significant amounts of lead and silver and could be a useful raw material for European lead smelters or Pasminco itself. In 1998, Budelco started to build the new installation (costs about 50 million USD). It converted its zinc production to low-iron zinc concentrates early 2000 [9].

4. Analysis of conditions influencing waste handling in Dutch zinc production

As indicated above, the solution directions studied were respectively the following: increased jarosite storage capacity in new better sealed jarosite ponds, the jarosite (co-)treatment process, and the input of low-iron zinc concentrates in primary zinc production.

Taking the earlier mentioned categories of drivers and barriers of technology development into account, the following conditions seem to influence waste handling at Budelco's zinc production.

In order to tackle the jarosite problem, the environmental manager of Budelco negotiated with the provincial authorities about a license to build a new jarosite tailing pond to enlarge the jarosite storage capacity and to solve the jarosite problem for the time being. When it became almost impossible to obtain such a license due to growing external pressures of provincial and national authorities, local political parties, the employees unions, nature conservation and local and provincial environmental groups, consumer associations, and the neighbors to the company, Budelco's management, together with its technical staff, searched for other solutions to the jarosite waste problem. Accordingly, Budelco's social embeddedness complicates its license-to-operate, and due to the increased social and environmental external pressures continuous incremental improvements of the zinc production process were not sufficient anymore.

Budelco has not traditionally been a research and technology oriented company but a cost center producing zinc. It has a small research and development department of its own, mainly used for troubleshooting and straightforward technical problems in the zinc plant. In addition, Budelco's process researchers can make use of Pasminco's research center.²⁵ Accordingly, the process researchers of Budelco had external contacts about various waste handling options with Pasminco's researchers, Delft

²⁵ Formed in 1989, Pasminco's Research Centre does research and gives technological support in the areas of mineral processing, process control, furnaces/sintering/roast/leach/purification/electrolysis and casting products. As well as being the focal point for process support and technological improvements in all operations, it studies fundamentally new methods of electrolysis, direct leaching and solvent extraction of zinc. It employs about 40 people [20].

University, public research institute and international metals producing firms. In order to find more definitive solutions for the jarosite waste problem, the ‘Steering Group Budelco’ was formed at national level, a relatively dense network, consisting of many heterogeneous actors.

Furthermore, Budelco was member of the international Jarosite Working Group, in which researchers from various zinc producing companies were participating. This Group focused on joint efforts on jarosite treatment. Thus, the process researchers of Budelco could make use of the resources of this already existing network structure consisting of heterogeneous technical process experts of various zinc producing firms to gain new information and experiences about jarosite treatment methods. It was a kind of informal know-how trading and open consultation between the researchers. This means that innovation takes place in an embedded network of heterogeneous researchers and engineers.

Accordingly, the development of the Oxysmelt jarosite treatment process resulted to a large extent from the open structure and the informal, heterogeneous interactions between the members of the Jarosite Working Group. Outokumpu had an especially central role in the development of the jarosite treatment process, having substantial knowledge of and a long time experience with pyrometallurgical oxysmelt processes, amongst others with its analogous copper flash smelting technology, functioning as a kind of innovation champion.

Co-treatment with other waste streams (such as oil and sludge) would have been a solution to make jarosite treatment economically viable, but the network interactions around this co-treatment option were not coherent and strong enough, as some parties were not willing to cooperate in this technology network. Irreversible treatment trajectories were already in-working for both the waste oil and the sludge streams. Thus, in addition to economic arguments it could be said that the jarosite treatment process was not further developed because Budelco’s management failed to enroll the crucial external parties in the network around the co-treatment process.

Concerning the low-iron containing zinc-ore of the Century mine, a network consisting of the regional Australian authorities (Queensland Government), the Dutch national and provincial authorities, Budelco, Pasminco, and the Century mine representatives was formed. Later on, the local Aboriginals communities also became a serious partner in the negotiation process. The Gulf Communities Agreement with the Aboriginals was a resolute condition, highlighting the need to involve all parties in the negotiating process around the exploitation of the Century mine, because the future of Budelco was totally dependent on the Australian low-iron-containing zinc concentrate.

According to the formal business structure, Pasminco is both the owner of the Century mine and of Budelco. This ownership relation gave Budelco already some control over the new mining project and guarantees Budelco’s low-iron zinc-ore supply for a long time. This gave rise to a change in materials, with other ‘Verlustrohstoffe’ included. Furthermore, Budelco’s process researchers had easily access to Pasminco’s process knowledge and experience due to this ownership relation, and they developed together with the process researchers and technical specialists of Pasminco the process adaptations needed at Budelco’s zinc plant to feed the low-iron-containing zinc concentrate.

5. Concluding remarks

Since the early 1980s, management of the jarosite waste presented a huge problem to the Dutch zinc production company Budelco. Over time, it has considered three types of solution directions.

Firstly, no change or continuous improvement of its current zinc production process, to be enabled by the construction of a new jarosite tailing pond that would increase the jarosite storage capacity. Secondly, the development of an in-process technological change, i.e. the Oxysmelt jarosite (co-)treatment process. And thirdly, the application of low-iron-containing zinc-ore in the production process.

The internal actor network, at the processing site notably Budelco's management, initially negotiated to arrive at on an incremental solution to the jarosite problem. When this solution had to be rejected due to increasing pressure of external actors, such as regulatory authorities, environmental groups and neighbors, the management of Budelco had to look for more radical solution directions. The Jarosite Working Group can be considered a firm-exceeding network, in which both firm-internal and firm-external technical experts were negotiating informally to arrive at more radical solutions for the jarosite problem. Indeed, a technologically feasible solution was identified by the Group, the Oxysmelt jarosite co-treatment process. Its development, however, was blocked by lack of capital, excessive operational costs and conflicting interests and power exertion of some crucial external parties. These had formed an alternative network that supported another controversial solution.

Another actor-network was at work at and around the ore winning site(s). In addition to the actors directly involved, such as Budelco, the holding company Pasminco, the regulatory bodies, and the environmental groups, the negotiation on the exploitation of the low-iron zinc-ore showed that the influence of certain firm-external actors upstream the production chain near the ore mining activities such as the local Aboriginal communities, also had to be taken into account.

In order to get more insight into the way embedded industrial production systems can meet the sustainability challenge, we studied the conditions that influenced the development and implementation of waste management options in a Dutch zinc production company. These conditions appear to be a combination of technological capability and embedding (proven technology versus in-process innovations versus change in ore material), economics (investments, depreciation times, operational costs), and network formation and actor acceptance (social embeddedness).

The low-iron containing zinc-ore appears to be the most environmentally friendly option to manage the jarosite waste problem because no new jarosite waste is formed at all. This option, however, only temporarily meets the sustainability challenge. The Century mine has a limited life span and its capacity is by far not sufficient as input material for the primary zinc production industry worldwide. Furthermore, when processing this ore, no jarosite treatment process is developed nor implemented at the Budelco site. Thus, the jarosite waste already formed and stored at Budelco remains untreated. In addition, at zinc producing plants throughout the world that do not have access to low-iron-containing zinc concentrate—i.e. most of them—jarosite storage remains the only option. These storage locations represent not only sunk costs, but also sunken environmental problems.

To avoid passing the associated problem on to future generations, recycling activities, secondary zinc production and closed loop zinc production must be the objective in the development of new technologies for the management of the waste problems of primary zinc production. This requires coherent network building between the various embedded metals production industries that are interconnected. Primary zinc production delivers an iron-bearing waste stream. In principle, somehow this ought to be input to the steel industry and today the secondary steel producing industry delivers a zinc-containing waste, which ought to be reprocessed in zinc smelters. Many steel producers, however, refuse to use iron-bearing residues from the zinc industry in their production process, because of the very high quality standards of their input material and the detrimental effect zinc may have on their installations.

In conclusion, the following conditions influenced waste management innovations in an embedded zinc production system.

The degree of external social pressure put upon the zinc production system is important: increased environmental pressure lead to the perception of an actual crisis at the existing zinc production system with regard to handling its jarosite waste stream.

The availability of a sophisticated firm-internal technology network of actors plays an important role. As Budelco didn't have a large research department with a high density of technical specialists, interactions with and enrolment of various firm-external actors and resources was very important.

Access to more externally oriented networks, consisting of heterogeneity of actors (and resources) was critical for the development of the jarosite treatment solution direction. The Steering Group, the co-treatment group and especially the Jarosite Working Group were examples of such externally oriented networks. Another example is the network around the low-iron-containing zinc-ore option, consisting of heterogeneous actors and diverse interactions. Furthermore, it is supposed that the highly intertwined physical and organizational infrastructure of Budelco, including various parties with vested and often conflicting interests, complicated the actual implementation of the jarosite co-treatment process to a large extent. The technical and organizational (social) embedding of the new technology is a crucial condition for its implementation.

The studied options of managing the jarosite waste problem show that even if potential solution directions are available, the choices between them depend on the formation and interactions of the social networks, in which various firm-internal actors and firm-external actors negotiate an agreement on the preferred solution direction.

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