CHEMICAL ENGINEERING TRANSACTIONS
VOL. 70, 2018

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš
Copyright © 2018, AIDIC Servizi S.r.l.
ISBN 978-88-95608-67-9; **ISSN** 2283-9216

DOI: 10.3303/CET1870036

Industrial Symbiosis: A Case Study Involving a Steelmaking, a Cement Manufacturing, and a Zinc Smelting Plant

Miguel Afonso Sellitto*, Fábio Kazuhiro Murakami

Unisinos, Av. Unisinos 950 São Leopoldo 93.022-000, Brazil
sellitto@unisinos.br

Industrial Symbiosis is the part of Industrial Ecology that manages environmental and economic improvements through the exchange of materials, resources, utilities, and by-products between members of a network of companies, such as supply chains or technological clusters. The purpose of this article is to analyze the mutual exchange of materials that occur among a steelmaking plant, vendors, and other business partners in a network of industrial companies. The research object is a steelmaking plant of Brazil. Almost 100 % of the raw material of the steelmaking industry is metallic scrap originated from other industries. Likewise, the steelmaking industry routes almost 100 % of the waste to other companies provided there is commercial and logistical feasibility. Seven major companies form the network, but this study involves only three companies. The complete study involves the entire network. This study involves a steelmaking plant, that generates by-products (slag, electric arc furnace dust, mill scale, and zinc sludge) used by a cement plant and a zinc smelting plant as raw materials. The zinc smelting plant closes the loop of the circular economy, as the sludge serves as raw material for zinc ingots used by the steelmaking plant in the galvanization process of its wire rod manufacture. The study concluded that synergetic relationships of mutual interest are the main factor that drives the industrial symbiosis in the network. Environmental aspects are also relevant. Even existing mutual interest, industrial symbiosis strongly depends on external factors, like logistics and legal compliance. The companies must rely on intermediate transportation companies that usually have difficulties to comply with the legislation and rarely has competitive costs or high production scale.

1. Introduction

The generation of industrial waste and the use of natural resources by manufacturing companies usually contribute to the degradation of the environment, with severe environmental and economic consequences (Sellitto, 2018). To avoid such consequences, recent environmental regulations force manufacturing companies to control the impact of its operations (Chaabane et al., 2012), which include the entire supply chains (SC), from the extraction of raw material until the return of used goods or final disposal of waste (Linton et al., 2007). Therefore, environmental control became strategic for SC, mainly due to the costs associated with losses, waste, and penalties imposed by the legislation, as well as the need to maintain a corporate image of an environmental-friendly company (Hicks et al., 2004). The research on sustainable development in SC includes Industrial Symbiosis (IS), a collective initiative in which waste and by-products of a company turn into low-cost raw materials and fuels to other companies. It helps companies of a network to improve the environmental and economic collective performance by the mutual exchange of wastes, by-products (Costa and Ferrão, 2010) and unrecovered energy (Belaud et al., 2017).

The steel industries can play an important role in IS. The ability to process industrial waste and to generate recyclable by-products favors the implementation of IS in the industry (Vadenbo et al., 2013). In the past, the steelmaking industry created a corporative image of an old-fashioned and dirty industry. Instead, steel is a flexible component with a wide spectrum of applications in various industries, its fabrication process employs almost only returned waste from other industries, and the by-products generated are almost all routed to other industries as raw materials or fuel (Mackillop, 2009). Since 1990, steelmaker companies integrated their environmental and business strategy to enjoy economic opportunities as well as to comply with regulations and stakeholders´ pressures (Singh et al., 2008).

Please cite this article as: Sellitto M.A., Murakami F.K., 2018, Industrial symbiosis: a case study involving a steelmaking, a cement manufacturing, and a zinc smelting plant , Chemical Engineering Transactions, 70, 211-216 DOI:10.3303/CET1870036

This article focuses on the intertwined use of by-products of a steelmaking company and some of their business partners. Previous studies focused mainly on the recycling of the waste generated in the steel industry. This article goes beyond and also focuses on the use of by-products received from vendors in the steel industry, characterizing a closed-loop movement. Monshi and Asgarani (1999) analyzed the use of steel slag as raw material for the production of Portland cement. For various industrial applications, a hydrometallurgical process recovers efficiently the zinc present in the electric arc furnace (EAF) dust (Shawabkeh, 2010). Some regional studies are also relevant. Brassioli et al. (2009) analyzed the used of the slag in agriculture as acidity corrector during the sugarcane planting in Brazil. Dalmaso (2011) did the same analysis in the Pampean region of Argentina. Corrêa et al. (2008) highlighted the increase of productivity in the soybean culture with the application of steel slag in the tillage system. Melloni et al (2001) analyzed the use of Electric Arc Furnace (EAF) dust in the soybean culture. Santos et al. (2006) did the same analysis in the corn culture. Luz et al. (2006) focused on the integration of different initiatives regarding the reuse of steel waste. A complete, compared analysis will be made in the further research.

The research problem that this article poses is: What kind of mutual materials exchange can a steelmaking plant and their business partners permanently sustain? The purpose of this article is to analyze the mutual exchange of materials that occur among a steelmaking plant, vendors, and other business partners in a network of industrial companies. The secondary objectives are (i) to identify the by-products that the steelmaking plant routes to and receives from other companies and (ii) to identify the implications and the managerial decisions that support this mutual exchange. The study involves a steelmaking plant, the focal company that generates by-products (slag, electric arc furnace dust, mill scale, and zinc sludge) used by a cement manufacturer and a zinc smelter as raw material. The zinc smelter closes the loop. The sludge serves as raw material for zinc ingots supplied to the steelmaking plant as raw material for the manufacturing of wire rod performed by the plant.

2. Industrial Symbiosis

Mutual interactions between industrial companies occur in three hierarchical levels: (i) the company level (eco-design, green manufacturing, etc); (ii) the network or regional level (IS, life cycle analyses, etc.); and (iii) the global level (GSCM applied to global SC). This study focuses on the network level, mainly at Industrial Symbiosis (IS) practices. IS involves physical exchange of materials, energy, water, and by-products between companies with some degree of similarity (Chertow, 2000). In the IS context, recycling of industrial waste reduces the consumption of natural resources and the environmental impacts resulting from the extraction of virgin material. Mostly, the involved organizations belong to the same network, as technological parks (Sellitto et al., 2017), industrial clusters (Sellitto et al., 2018), or SC (Sellitto et al., 2015).

The term industrial symbiosis comes from the biology concept of symbiosis or mutualism (Fraccascia et al., 2017), in which two or more different species exchange materials, energy, or information aimed at achieving mutual benefits from the exchange (Chertow, 2000). Transferring this concept to inter-firm relationships, a collaboration between firms can produce mutual benefits that many times are larger than those provided by individual strategies. Common, mutual benefits include social and environmental, as well as economic ones (Chertow, 2000). IS does not necessarily take place only within the limits of the network. In technological or eco-industrial parks or in industrial clusters, due to the strong proximity of the players, the effect of the mutual benefits of IS usually affects an entire geographical region (Tudor et al., 2007), reinforcing the importance of the park or the cluster in the local or regional development (Sellitto and Luchese, 2018).

Previous studies focused on IS in industrial networks can provide useful information. Jacobsen (2006) studied Kalundborg, a Danish industrial park in which companies exchange by-products as raw materials and fuels. Wang et al. (2017) studied the Styrian recycling network in Austria. Beers et al. (2008) analyzed the potential for the reuse of by-products, water, and the exceeding energy produced at Kwinana and Gladstone, in Australia. Yuan and Shi (2009) assessed the potential of a zinc smelter for IS. Costa et al. (2010) studied public policies on IS in Denmark, England, Portugal, and Switzerland. Dong et al. (2013) evaluated the economic and environmental gains in three Chinese SC of the steel industry. Marinous-Kouris and Mourtsiadis (2013) identified patterns and limitations in 16 eco-industrial networks in Greece. Liao and Ma (2013) demonstrated that IS reduced substantially the emissions of GHG in an electro-electronic industrial park in Taiwan.

Regarding motivation and drives, Chertow (2000) states that implementations of IS in networks usually focus mainly on cost reduction, as the companies can receive waste as raw material and fuel at lower cost, which is supported by empirical evidence (Dong et al., 2013). Other motivations are the scarcity of natural resources (Wang et al., 2017), the creation of a positive corporate image (Jacobsen, 2006), and the need to comply with local regulations (Costa et al., 2010). Therefore, under certain circumstances, IS can contribute to increasing the capacity of an SC to compete and to survive in the industry (Sellitto et al., 2011).

3. The Research: Methodology and Results

The study required a two-folded method. The first step involved a literature review that identified the most critical factors that limit or stimulate IS. The review organized the factors in external (Walker et al., 2008) and internal constructs (Testa and Iraldo, 2010). The external constructs are cost reduction (Luthra et al., 2011) and compliance with legislation (Liao and Ma, 2013). The internal constructs are trading concerns (Pereira et al., 2011) and market knowledge (Mirata and Emtairah, 2005). In the second step, to evaluate the intensity of the constructs, the study developed a case study in three out of the seven companies of a network.

The companies are a semi-integrated steelmaking plant (SP) that uses metal scraps as raw material and produces wires and rods, a cement manufacturer (CM) that produces Portland cement, and a zinc smelter (processes ZS1 and ZS2) that produces Special High-Grade Zinc (SHG). All the companies are located in Southern Brazil. SP produces circa 300,000 t/y. CM produces circa 400,000 t/y. ZS produces circa 525,000 t/y. The main by-products of SP are steel slag (circa 144,000 t/y), electric arc furnace (EAF) dust (circa 6,000 t/y), mill scale (circa 9,600 t/y), and zinc sludge (circa 360 t/y). SP supplies CM with mill scale, ZS1 with zinc sludge, and ZS2 with EAF dust. The complete study will include the steel slag. ZS1 uses the returned sludge to produce zinc ingots to SP. Figure 1 represents the dyadic relationships focused on this study. In the figure, SP produces mill scale, zinc sludge, and EAF dust, routed respectively to CM, ZS1, and ZS2. Closing a loop, ZS1 uses the sludge to produce ingots of zinc SHG, supplied to SP.

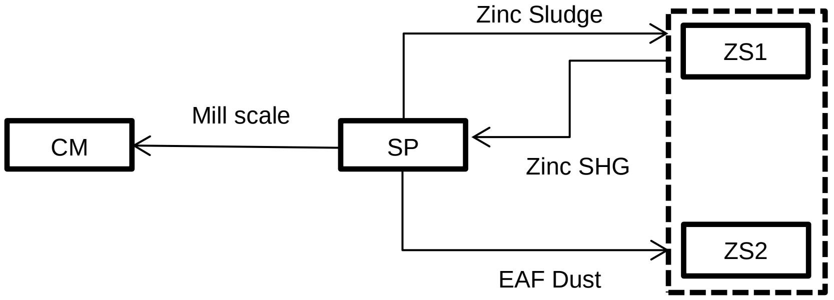

Figure 1: The network and the exchange material relationships

3.1 Relationship 1: SP and CM

SP operates casting, rolling, and forging manufacturing processes whose main by-product is mill scale, a waste formed by the iron oxide generated by the oxidation of the steel ingot surface when the ingot exits the casting machine or the reheating oven and meets cold air. The metal at high temperature reacts with the oxygen to form iron oxides with low adhesion, which constitute the mill scale. The reduced particle size of the waste limits the internal reuse. Therefore, parts of the generated material routes to different applications as the cement manufacturing plant.

Mill scale has a low price (about $ 40.00/t), which limits the application to nearby destinations. As SP and CM are very close (less than 10 km), the logistics cost has little importance in the application. SP has full responsibility for the shipping and temporary warehousing of the by-product. SP generates permanently the waste. The availability of the mill scale is higher than the requirement of CM, so the adjusted price is very low. Moreover, SP prospects permanently new applications for the by-product, mostly regarding the fabrication of concrete artifacts. The companies have a formal permanent contract to rule the relationship.

Mill scale can partially replace iron ore in the cement manufacturing. It also serves as filler or as a partial substitute (up to 40 %) for sand in the manufacture of concrete artifacts, such as pipes and pave pieces, and in mortars. The use of recycled mill scale reduces significantly the cost of both operations. In CM, it reduces the extraction of iron ore and sand and significantly extends the lifetime of lime and sand quarries and deposits. In SP, it eliminates the need to dump to controlled landfills.

3.2 Relationship 2: SP and ZC

ZC1 supplies zinc ingots for the production of galvanized wire by an electroplating process, which coats the wire with zinc, preventing corrosion. The electroplating process produces a by-product, the zinc sludge. Priory, SP dumped the sludge in controlled landfills. Currently, the sludge returns to ZC1 as raw material for zinc ingots supplied to SP. Due to the distance (circa 1,000 km), logistics cost is important and limits the application. A contract between the companies rules the exchange of materials. The price of the by-product fluctuates accordingly with international prices issued by the London Metal Exchange, which provides revenue for SP instead of the prior cost of dumping at landfills. The companies integrated reverse and direct logistics. Only vehicles that brought ingots carry sludge.

The sludge is a raw material for the production of SHG zinc in the form of granules, ingots, or jumbos, used to produce alloys (brass, bronze) and in electroplating processes. SP uses only ingots. All of the zinc produced by ZC1 comes from sludge generated by its own customers, such as SP. The production from concentrate zinc or exclusively from extracted materials is not economically feasible. Therefore, the cost reduction provided by the recycling helped the company to construct an advantage in the industry.

SP also produces EAF dust, a hazardous waste consisting of metal oxides such as zinc, chromium, lead, and cadmium. A dedusting system based on sieve filters captures almost 100 % of the EAF dust. Part of the EAF dust routes to ZC2, part routes to companies that produce zamak alloys. SP dumps the exceeding part to controlled landfills. ZC2 volatilizes and leaches the zinc in the EAF dust in an oven, by the Waelz process. During the process, the EAF dust mixes with coal, limestone, and silica, dries and preheats to volatilize the alkali halides, reducing the zinc, lead, and cadmium oxides. The final product is zinc oxide. ZC2 does not supply SP with raw materials. Due to the distance and the high logistic cost, the shipping from SP to ZC2 is not permanent, depending on opportunities associated with the returning freight. A regular flow of products and by-products does not exist and the IS involving ZC2 is incomplete.

Table 1 summarizes the findings, highlighting the similarities according to the four constructs.

Table 1: Summary of the findings and similarities among them

By-product	Cost	Compliance	Trading	Logistics
Mill scale	Both parts achieved large benefits. SP no longer needs to dump 800 tonnes per month to landfills. CM reduced substantially the extraction of virgin material from quarries.	The legislation allows dumping to controlled landfills, under severe restrictions, requiring permanent monitoring. Recycling allows full compliance with current legislation.	SP considers the by-product as a regular product, requiring a formal contract. As SP offers more than CM can receive, the price is very low.	The recycling requires a specific license to the transportation, which raises the cost and strongly limits new applications. Anyway, transportation is easier than dumping to landfills.
Zinc sludge	Both parts benefit. The recycling reduces the cost of zinc ingots. SP reduced the cost of dumping to landfills. ZS reduced the cost of acquisition of virgin materials.	The legislation allows dumping to controlled landfills, under severe restrictions, requiring permanent monitoring. Recycling allows full compliance with current legislation.	SP and ZS have a formal contract involving the by-product and new supplies. International market regulates the price of the sludge, so the price is high.	The logistics is a severe restriction for new applications, due to the regulations to long-distance shipping as well as the higher than usual cost. Dumping to landfills would be easier.
EAF dust	Both parts benefit. The recycling reduces the cost of zinc oxides. SP eliminated the cost of dumping to landfills. ZC2 reduced the cost of raw materials.	The legislation allows dumping to controlled landfills, under severe restrictions, requiring permanent monitoring. Recycling allows full compliance with current legislation.	The companies do not have a contract, as SP does not buy from ZC2. The dyadic relationship is case-to-case, negotiating each shipping under specific conditions.	The logistics is a severe restriction for new applications, due to the regulations to long-distance shipping as well as the higher than usual cost. Dumping to landfills would be easier.

Regarding cost, in all cases both parts benefit with the relationship. Regarding compliance with the legislation, in all the cases, the companies face severe restrictions and this is an important issue to handle in future expansions of the activities. Regarding trading details, when there is a regular, permanent flow of materials, the companies chose to formalize the buying- supplying relationship by contracts. When the flow in not regular, shipments occur on demand. Finally, logistics is a severe restriction for long distances, which encourages companies to dump their co-products in nearby controlled landfills.

4. Conclusions

The study answered the research question. A dyadic relationship between companies can stimulate the practice of IS if it creates a strong synergy, with mutual gains, if it allows full compliance to the legislation, and if the logistics does not jeopardize the feasibility. Trading conditions (hiring or contracting assurances) seems to be less relevant to the result.

The study unveiled similarities that serve to formulate hypotheses to further, deeper studies aiming at verifying supporting to IS in networks. In all cases, both companies experienced important economic gains. In the case of the mill scale, the gains are substantial. The producer stops dumping the by-product and the receiver stops buying virgin material. Therefore, the first hypotheses H1 is: to foster IS in a network, all partners must have economic gains. In all cases, despite the severity and the need for permanent monitoring, the legislation favors recycling. Therefore, the second hypotheses H2 is: to foster IS in a network, the current legislation must stimulate recycling, even establishing rigorous safety requirements, such as monitoring or assessing environmental conditions of the operations. In the case of the mill scale and zinc sludge, companies have formal, permanent contracts. The shipment of EAF dust occurs only when there is a request by ZS1, which occurs randomly. Market forces regulate prices. As the relationship is unbalanced, benefits to one part often occur. The third hypotheses H3 is: the existence of a formal contract between parts is irrelevant to foster IS in a network. In all cases, logistics is a strong determinant of the success of the relationship. In the case of the mill scale, the low cost of the logistics favors the shipping, which is more convenient than dumping to landfills. In the other cases, the companies avoid dumping to keep eco-efficiency, even if the logistics cost is high. To improve IS, some intermediate solution as warehousing and integration with other flows must provide scale to the operation or increment the amount of recycling material. Finally, the fourth hypotheses H4 is: to foster IS in a network, the companies must manage logistics according to a common, diversified strategy.

The next article will embrace the full study, with seven companies and a deeper analysis. The full study includes a numerical analysis of the complexity and systemic effects observed in the network and the influence of IS in the surrounding area and in the regional development.

Acknowledgments

The Brazilian Research agency CNPq funded the complete study under the grant number 303574/2016-0.

References

Beers, D., Bossilkov, A., Corde, G., Berkel, R. 2008, Industrial Symbiosis in the Australian Minerals Industry: The Cases of Kwinana and Gladstone, Journal of Industrial Ecology, 11, 55-72.

Belaud, J., Adoue, C., Sablayrolles, C., Vialle, C., Chorro, A., 2017, Decision making approach for industrial ecology: layout and commercialization of an industrial park, Chemical Engineering Transactions, 57, 1561-1566

Brassioli, F., Prado, R., Fernandes, F. 2009, Agronomical evaluation of the steel slag in five cycles of the sugarcane plantation, Bragantia, 68, 381-387. (in Portuguese)

Chaabane, A., Ramudhin, A., Paquet, M. 2012, Design of sustainable supply chains under the emission trading scheme, International Journal of Production Economics, 135, 37-49.

Chertow, M. 2000, Industrial symbiosis: literature and taxonomy, Annual Review of Energy and the Environment, 25, 313-337.

Corrêa J., Büll L., Crusciol C., Tecchio M., 2008, Superficial application of slag, clay, lime, sewage sludge and calc in the soybean culture, Pesquisa agropecuária brasileira, 43, 1209-1219. (in Portuguese)

Costa I., Ferrão P., 2010, A case study of industrial symbiosis development using a middle-out approach, Journal of Cleaner Production, 18, 984-992.

Costa, I., Massard, G., Agarwal, A., 2010, Waste management policies for industrial symbiosis development: case studies in European countries, Journal of Cleaner Production, 18, 815-822.

Dalmaso, D., 2011, Utilization of steel slag in agriculture soils in the argentine Pampean region, Usos del Acero – ILAFA, 1, 30-33. (in Spanish)

Dong, L., Zhang, H., Fujita, T., Ohnishi, S., Li, H., Fujii, M., Dong, H., 2013, Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki’s experience and practice in Liuzhou and Jinan, Journal of Cleaner Production, 59, 226-238.

Fraccascia, L., Albino, V., Garavelli, C. 2017, Technical efficiency measures of industrial symbiosis networks using enterprise input-output analysis, International Journal of Production Economics, 183, 273-286.

Hicks, C., Heidrich, O., Mcgovern, T., Donelly, T., 2004, A functional model of supply chains and waste, International Journal of Production Economics, 89, 165-174.

Jacobsen, N., 2006, Industrial symbiosis in Kalundborg, Denmark: a quantitative assessment of economic and environmental aspects, Journal of industrial ecology, 10, 239-255.

Liao, M., Ma, H., 2013, The potential environmental gains from industrial symbiosis: Evaluation of CO2 reduction through a crucial by-product, International Journal of Applied Environmental Sciences, 8, 129-136.

Linton, J., Klassen, R., Jayaraman, V., 2007, Sustainable supply chains: an introduction, Journal of Operations Management, 25, 1075-1082.

Luthra, S., Kumar, V., Kumar, S., Haleem, A., 2011, Barriers to implement green supply chain management in automobile industry using interpretive structural modeling technique-An Indian perspective, Journal of Industrial Engineering and Management, 4, 231-257.

Luz, S., Sellitto, M., Gomes, L. 2006. Environmental performance measurement supported by a multicriterial approach: a case study in a manufacturing operation in the automotive industry, Gestao & Producao, 13, 557-570.

Mackillop, F., 2009, The construction of 'waste' in the UK steel industry, Journal of Environmental Planning and Management, 52, 177-194.

Marinos-kouris, D., Mourtsiadis, A., 2013, Industrial symbiosis in Greece: A study of spatial allocation patterns, Fresenius Environmental Bulletin, 22, 2174-2181.

Melloni, R., Silva, F., Moreira, F., Neto, A., 2001, Electric arc furnace dust in the soil mycrobiota and in the soybean growing, Pesquisa agropecuária brasileira, 36, 1547-1554. (in Portuguese)

Mirata, M., Emtairah, T., 2005, Industrial symbiosis networks and the contribution to environmental innovation, Journal of Cleaner Production, 13, 993-1002.

Monshi, A., Agarani, M., 1999, Producing Portland cement from iron and steel slags and limestone, Cement and Concrete Research, 29, 1373-1377.

Pereira, G., Sellitto, M., Borchardt, M., Geiger, A., 2011, Procurement cost reduction for customized non-critical items in an automotive supply chain: An action research project, Industrial Marketing Management, 40, 28-35.

Santos, G., Berton, R., Camargo, O., Abreu, M., 2006, Zinc availability for corn grown on an oxisol amended with flue dust, Scientia Agricola, 63, 558-563.

Sellitto, M., 2018, Assessment of the effectiveness of green practices in the management of two supply chains, Business Process Management Journal, 24, 23-48.

Sellitto, M., Borchardt, M., Pereira, G., Gomes, L., 2011, Environmental performance assessment in transportation and warehousing operations by means of categorical indicators and multicriteria preference, Chemical Engineering Transactions, 25, 291-296.

Sellitto, M., Luchese, J., 2018, Systemic Cooperative Actions among Competitors: the Case of a Furniture Cluster in Brazil, Journal of Industry, Competition and Trade, 1-16 (online first).

Sellitto, M., Pereira, G., Borchardt, M., Silva, R., Viegas, C., 2015, A SCOR-based model for supply chain performance measurement: application in the footwear industry, International Journal of Production Research, 53, 4917-4926.

Sellitto, M., Pereira, G., Marques, R., Lacerda, D., 2017, Systemic Understanding of Coopetitive Behaviour in a Latin American Technological Park, Systemic Practice and Action Research, 1-16 (online first).

Shawabkeh, R., 2010, Hydrometallurgical extraction of zinc from Jordanian electric arc furnace dust, Hidrometallurgy, 104, 61-65.

Singh, R., Murty, H., Gupta, S., Dikshit, A., 2008, Integrated environment management in steel industries, International Journal of Management and Decision Making, 9, 103-128.

Testa, F., Iraldo, F., 2010, Shadows and lights of GSCM (Green Supply Chain Management): determinants and effects of these practices based on a multi-national study, Journal of Cleaner Production, 18, 953-962.

Tudor, T., Adam, E., Bates, M., 2007, Drivers and limitations for the successful development and functioning of EIPs (eco-industrial parks): A literature review, Ecological Economics, 61, 199-207.

Vadenbo, C., Boesch, M., Hellweg, S., 2013, Life cycle assessment model for the use of alternative resources in ironmaking. Journal of Industrial Ecology, 17, 363-374, 2013.

Walker, H., Di Sisto, L., Mcbain, D., 2008, Drivers and barriers to environmental supply chain management practices: lessons from the public and private sectors, Journal of Purchasing and Supply Management, 14, 69-85.

Wang Z., Jiang Y., Huang Y., Jia X., 2017, Complex network method towards evaluating industrial symbiosis, Chemical Engineering Transactions, 61, 169-174

Yuan, Z., Shi, L., 2009, Improving enterprise competitive advantage with industrial symbiosis: case study of a smeltery in China, Journal of Cleaner Production, 17, 1295-1302.