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Industrial Ecosystems and Food Webs: An Ecological-Based Mass Flow Analysis to Model the Progress of Steel Manufacturing in China

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ABSTRACT

Materials and energy are transferred between natural and industrial systems, providing a standard that can be used to deduce the interactions between these systems. An examination of these flows is an essential part of the conversation on how industry impacts the environment. We propose that biological systems, which embody sustainability, provide methods and principles that can lead to more useful ways to organize industrial activity. Transposing these biological methods to steel manufacturing is manifested through an efficient use of available materials, waste reduction, and decreased energy demand with currently available technology. In this paper, we use ecological metrics to examine the change in structure and flows of materials in the Chinese steel industry over time by means of a systems-based mass flow analysis. Utilizing available data, the results of our analysis indicate that the Chinese steel manufacturing industry has increased its efficiency and sustainable use of resources over time at the unit process level. However, the appropriate organization of the steel production ecosystem remains a work in progress. Our results suggest that through the intelligent placement of cooperative industries, which can utilize the waste generated from steel manufacturing, the future of the Chinese steel industry can better reflect ecosystem maturity and health while minimizing waste.

1. Introduction

Life has existed on Earth for more than 3.8 billion years. Through natural selection over millennia, organisms have continuously evolved with the natural environment into the systems that exist today. Through the adaptation and application of ecological principles to human engineered systems, there is the potential to increase efficiency through the intelligent use of energy and resources, in addition to producing an overall reduction of waste [1–4]. Investigating the natural structures by which biological systems organize themselves may provide a more intelligent, sustainable way of formulating systems within the global community. A sustainable global community is one that meets the needs of the present generation without sacrificing those of future generations [5].

Material and energy flows are the fundamental properties affecting environmental sustainability because they are the main physical link between industrial and natural systems [6]. Ecologists can derive multiple structure-based and flow-based metrics from these fluxes in ecosystems through the use of food webs. These metrics describe natural ecosystem structures, properties, and predator-prey relationships within an ecosystem [7,8]. In a similar way, this approach may be used to investigate how nature can provide insight into the creation and enhancement of sustainable, performance-driven engineered systems.

By using a systems-based analysis of the industrial landscape, it is possible to systematically model composite processes in order to design, project, and control mechanisms to produce a system that moves materials and energy more efficiently. In addition, this investigation unveils the stressors, response mechanisms, and environmental impacts of resource exploitation throughout the modeled system. Engineers can use this analysis to make modifications to the industrial structure by designing systems that more closely resemble a healthy ecosystem. Past examples of using measurements of system behavior to influence design changes within the system have been well documented [4,6,9]. Using the analyzed system's metrics, more efficient and effective network configurations have been found to meet the traditional network design goals of reduced cost and increased efficiency [2,3].

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Some scientists argue that the Chinese steel industry (CSI) is currently unsustainable [10], given the current high resource and energy demand of the CSI combined with the cumulative environmental degradation from years past. This paper aims to use a systems-based mass flow analysis (MFA) to model the CSI's progression in order to evaluate the system's performance and health using ecological metrics. We investigate historical integrated steel manufacturing starting from the time when China began to aggressively invest in widespread energy conservation programs in its industrial sector in the Sixth (1981–1985) and Seventh (1986–1990) Five-Year Plans [11]. Next, we examine the current widespread integrated steel manufacturing processes. Finally, we investigate future scenarios.

The steel industry is a pillar of the Chinese economy; however, rapid growth has come at a cost to the environment [12]. Chinese crude steel production has grown rapidly, increasing the output of steel from 31.8 million metric tons in 1978 to 821.99 million metric tons in 2013 [13]. Fig. 1 [13] depicts the increase in crude steel production from 2004 to 2013.

The steel industry accounts for 18.3% of total energy consumption and is one of the top three sources of greenhouse gas emissions from China [14]. In 2012, China accounted for 29% of the entire world's CO_2 emissions [15]; of these emissions, approximately 12% was directly due to steel manufacturing [16]. Thus, approximately 3.48% of global CO_2 emissions originate from Chinese steel manufacturing. The CSI has made significant progress toward conserving energy and the environment, although there is still considerable improvement to be made on an international scale. According to 2007 data, the International Energy Agency determined that China could save 6.1 $GJ{\cdot}t^{-1}$ of crude steel through the adoption of the best available technologies [17].

Traditional steel manufacturing involves two kinds of processes: the blast furnace (BF)-basic oxygen furnace (BOF) process, which is known as the "long process," or the electric arc furnace (EAF) process, which is known as the "short process." The long process involves procedures such as sintering, coking, and use of the BF, which produce far greater amounts of pollution than the short process, which is more reliant on scrap. China's high energy consumption and heavy pollution within its steel manufacturing industry are primarily due to a lack of scrap supply, which results in over 91% of the steel manufacturing to be reliant on the long process [18]. This paper investigates the steel product life-cycle on a systems level and evaluates the system's structure using ecologically inspired metrics in an effort to provide quantitative insight into potential areas for sustainable improvement.

2. Materials and methods

2.1. Structure-based metrics

Ecologists use an array of metrics to understand the links between ecosystem structure and the resulting behavior of ecological systems [19]. Perhaps the most common representation of material flows used today is the food web (FW), which is a graphical depiction of the linkages between actors within a given ecosystem. The calculation of these structure-based metrics involves the identification of predators, prey, and the links they represent within a particular FW. This method of representation can be shown in matrix form, with 1 denoting a successful link and 0 denoting the absence of a link, and with columns representing predators and rows representing prey (i.e., in Fig. 2 [4], $f_{ij} = 1$ represents a link between prey (i) and predator (j)). The species are numbered and listed above and beside the matrix to show that they are the same species across rows and columns. In this paper, we adapt the FW principle and subsequent matrix analysis to the steel industry in China in an effort to quantify the impacts and potential areas for improvement within its structure.

The structure-based metrics used in this study are defined below:

Number of species (N): The total number of species in an FW. This term is also commonly denoted as "species richness" and can be represented by the number of rows or columns in an FW matrix [20].

Number of links (L): The number of direct links between species in an FW. This term is represented by the number of non-zero interactions in the FW matrix [20].

$$L = \sum_{i=1}^{m}\sum_{j=1}^{n} f_{ij} \tag{1}$$

Linkage density (L_D): The ratio of the total number of links to the total number of species within a network [21].

$$L_D = L/N \tag{2}$$

Prey (n_{prey}): Species that are consumed by at least one other species. This relationship is represented by the number of non-zero rows within an FW matrix [21].

$$f_{row}(i) = \begin{cases} 1 & \text{for } \sum_{j=1}^{n} f_{ij} > 0 \\ 0 & \text{for } \sum_{j=1}^{n} f_{ij} = 0 \end{cases} \tag{3}$$

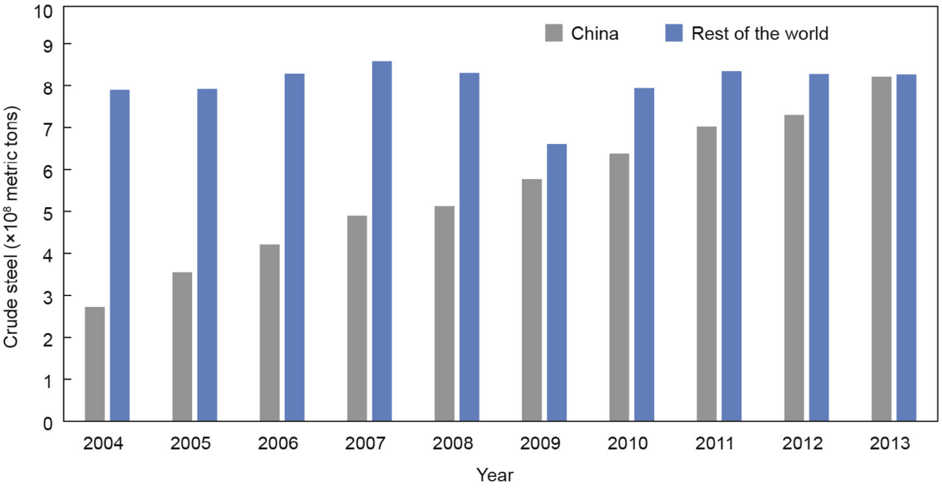
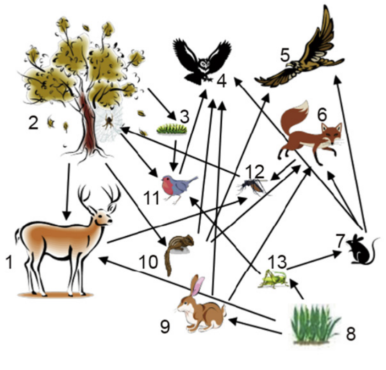


Fig. 1. Crude steel production (10^8 metric tons) in China and other countries. (Adapted from Ref. [13])



(a)

Predators

$$F = \text{Prey}\ \begin{array}{r|ccccccccccccc|}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 \\
\hline
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
2 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\
3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
7 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
8 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \\
9 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
10 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
11 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
12 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
13 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\
\hline
\end{array}$$

(b)

Fig. 2. (a) A hypothetical FW with numbers corresponding to species; (b) the FW matrix (F) representation of the hypothetical FW. (Adapted from Ref. [4])

$$n_{\text{prey}} = \sum_{i=1}^{m} f_{\text{row}}(i) \tag{4}$$

Predator (n_{predator}): Species that consume at least one other species. This relationship is represented by the number of non-zero columns in an FW matrix [21].

$$f_{\text{col}}(j) = \begin{cases} 1 & \text{for } \sum_{i=1}^{m} f_{ij} > 0 \\ 0 & \text{for } \sum_{i=1}^{m} f_{ij} = 0 \end{cases} \tag{5}$$

$$n_{\text{predator}} = \sum_{j=1}^{n} f_{\text{col}}(j) \tag{6}$$

Prey-to-predator ratio (P_{R}): The ratio of the number of species consumed by another species to the number of species that consume another species.

$$P_{\text{R}} = n_{\text{prey}} / n_{\text{predator}} \tag{7}$$

Generalization (G): The average number of prey consumed per predator within the FW. This is calculated by summing the columns in an FW matrix and then dividing by the number of columns containing non-zero elements (n_{predator}).

$$G = L / n_{\text{predator}} \tag{8}$$

Vulnerability (V): The average number of predators per prey in an FW. This is calculated by summing the rows in an FW and then dividing by the number of rows with non-zero elements (n_{prey}).

$$V = L / n_{\text{prey}} \tag{9}$$

Cyclicity ($\lambda_{\max}$): This is a measure of the strength and presence of cyclic pathways within the system. Cyclicity is calculated by finding the maximum real eigenvalue of the transpose of the FW matrix. The transpose of the FW matrix is A and I is the identity matrix [19,22].

$$\lambda_{\max} = \text{max, real eigenvalue solution to: } 0 = \det(A - \lambda I) \tag{10}$$

Connectance (C): The number of actual direct interactions (L) in an FW divided by the total number of possible interactions (N^2). If cannibalism is forbidden, then the number of possible interactions is diminished, resulting in the denominator becoming the fraction of non-zero off-diagonal elements in the FW [8,20,23].

$$C = L / N^2 \tag{11}$$

2.2. Flow-based metrics

Ecologists may also incorporate flow-based analysis to understand ecological systems. Flow-based metrics calculations require knowledge of both structural information and flow-based information. A flow-based analysis follows four different classes of flow:

(1) Inputs that enter across system boundaries;

(2) Flows that move between actors within the system boundaries;

(3) Exports that leave across the system boundaries; and

(4) Dissipation losses (most of which are associated with water or energy).

In contrast to the calculations of structure-based metrics, flow-based metrics calculations use an $(N+3) \times (N+3)$ FW flow matrix that includes inputs from outside the system (row zero), exports to outside the system (column $N+1$), and losses from the system (column $N+2$) (Fig. 3) [24]. A flow from actor i to actor j is represented as a real value by t_{ij}, which is the ith row and jth column entry in this matrix. A value of 0 for t_{ij} means that no material or energy flow occurs from actor i to actor j; thus, no link exists.

The flow-based metrics used in this study are defined below:

Total system throughput (TST_{p}): This is the sum of all flows in an ecosystem. TST_{p} is a measure of size or level of activity, and is

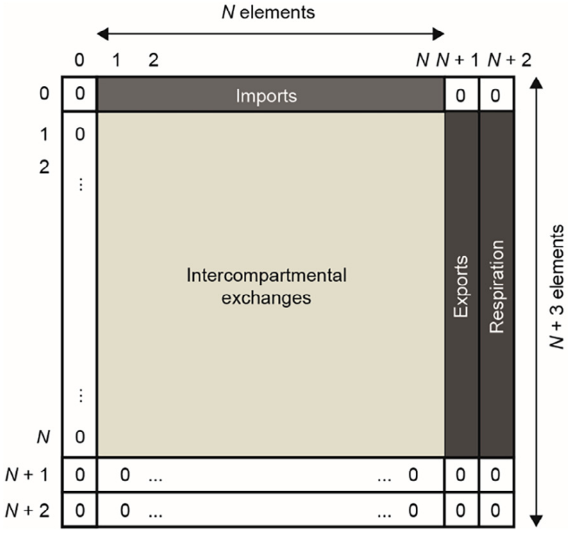


Fig. 3. Flow matrix example. (Adapted from Ref. [24])

thus comparable within this study to the gross national product (GNP), which estimates the overall economic activity of a nation [9,25,26].

$$\mathrm{TST_p} = \sum_{i=0}^{N+2}\sum_{j=0}^{N+2} t_{ij} \tag{12}$$

Average mutual information (AMI): This is the degree of specialization in the system or the number of constraints on the materials and/or energy flow. AMI has been suggested to be indicative of the developmental status, or level of system maturity, of an ecosystem [9].

$$\mathrm{AMI} = -k\sum_{i=0}^{N+2}\sum_{j=0}^{N+2}\frac{t_{ij}}{\mathrm{TST_p}}\cdot\log_2\left[\frac{t_{ij}\cdot\mathrm{TST_p}}{\left(\sum_{j=0}^{N+2}t_{ij}\right)\left(\sum_{i=0}^{N+2}t_{ij}\right)}\right] \tag{13}$$

System ascendency (ASC): This measures the amount of medium that an ecosystem distributes in an efficient way. Thus, it provides a single measurement of the growth and development inherent in the system [9,25,26].

$$\mathrm{ASC} = \mathrm{AMI}\cdot\mathrm{TST_p} \tag{14}$$

Development capacity (DC): This is the maximum potential that a system has at its disposal to achieve further improvement; it also serves as an upper bound for the ASC [9,25,26].

$$\mathrm{DC} = -1\cdot\sum_{i=0}^{N+2}\left[\left(\sum_{j=0}^{N+2}t_{ij}\right)\cdot\log_2\left(\sum_{j=0}^{N+2}t_{ij}\right)\right] \quad \mathrm{DC}\geq\mathrm{ASC}\geq 0 \tag{15}$$

Total system overhead (TSO): This pertains to redundant flows in the network and may be an indicator of the point of optimality between flexibility and efficiency [9,25,26].

$$\mathrm{TSO} = \mathrm{DC} - \mathrm{ASC} \tag{16}$$

Cycling index (CI) or Finn cycling index (FCI): This is a dimensionless number that accounts for the percentage of all fluxes that is generated by cycling, or the fraction of total activity in the system that is devoted to cycling [9,27].

$$\mathrm{TST_c} = \sum_{j=1}^{n}\left(\frac{t_{jj}-1}{t_{jj}}\right)T_j \tag{17}$$

$$\mathrm{CI} = \mathrm{TST_c}/\mathrm{TST_p} \tag{18}$$

where T_j contains the sum of flows in the input matrix columns, and $\mathrm{TST_c}$ is the total system cycled through flow.

Mean path length (MPL) or average path length (APL): This is the number of actors "visited" by a material or energy flow [27].

$$\mathrm{MPL} = \mathrm{TST_p}/\left(\sum_{j=0}^{N+2}t_{0j}\right) \tag{19}$$

Robustness (R): This measures the relationship between ASC and DC, or the organizational constraints in the system versus the redundancy, thus normalizing the system's "degree of order" [25,28].

$$R = -k\left(\frac{\mathrm{ASC}}{\mathrm{DC}}\right)\cdot\log_2\left(\frac{\mathrm{ASC}}{\mathrm{DC}}\right) \tag{20}$$

2.3. Steel industry application

As mentioned previously, some scientists argue that the current CSI is progressing on an unsustainable route. When evaluating this assertion, one cannot overlook the importance of the entire life-cycle of the finished product, because steel is the most recycled material in the world [13]. Metals do not degrade due to recycling; therefore, the flow of materials exiting the steel manufacturing process, and then being recycled later in the product's life in the form of scrap, is important in the flow analysis, especially in regards to feedback loops of material flows.

Fig. 4 illustrates the inputs of energy, water, raw materials, and scrap into the steel manufacturing process, along with the other processes involved in the life-cycle of steel. Understanding the full impact and uses of steel outside of the system boundaries of the steel manufacturing process results in a more accurate analysis of the systems within the network structure. To accurately model the changes in the steel manufacturing process, it is necessary to first define the system boundaries. Observing the transfer of core materials and energy makes it possible to investigate how the embedded processes within the boundaries have progressed over time.

2.3.1. Historical integrated steel manufacturing process

The energy consumption per metric ton of steel dropped by 20.9%, from 1285 to 1017 kgce·t^{-1} (1 kgce = 29.727 MJ·kg^{-1}) [29], from 1980 to 1990. During this time, China developed strategies

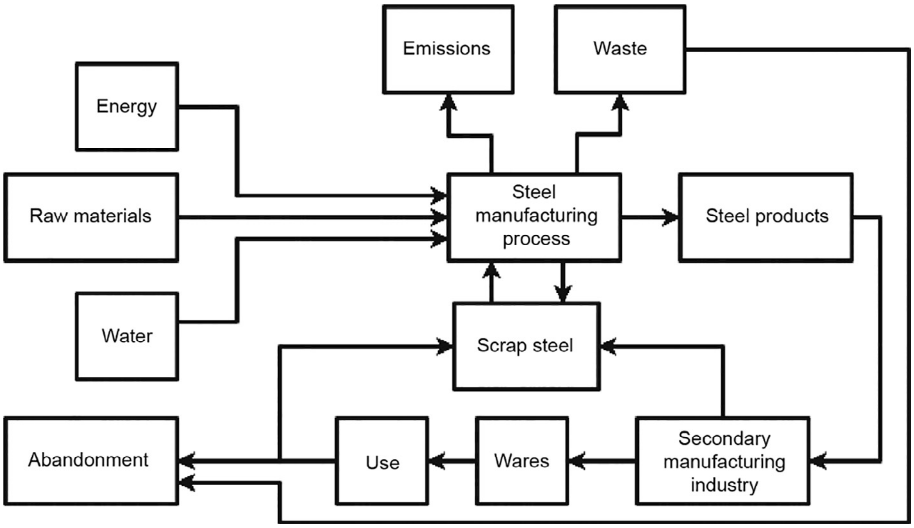


Fig. 4. Life-cycle flows of steel.

to improve energy efficiency and energy conservation management, offer financial incentives, direct R&D, initiate information technology services, and improve education and training [30]. Many of these strategies focus on optimizing the steelmaking process, and include retiring energy-intensive mechanical and electrical devices, incorporating new technologies such as continuous casting, and investigating the use of byproduct gases as fuel. For our historical analysis, we chose to use major process-level material flow values from the China Steel Development and Research Institute [31] for the 1988 Anshan Iron and Steel Group Corporation's BOF plants statistics. Values such as the coke rate, continuous casting yield, external scrap-use fractions, and each-stage material flow values in the production levels, as well as all model configurations, are listed in Supplementary Information S1. However, some values needed to be acquired from sources through the literature, as a single source could not be located. Fig. 5 demonstrates our simplified material flows for the CSI in 1987.

The raw material stores consist of raw water, lime, coal, and iron ore. The main processes contributing flows to the long process of steel manufacturing include the coking plant, sintering plant, lime plant, oxygen plant, and water-treatment plant. After the contributing flows, the core functions involved in the steel manufacturing process include coke making, sintering, BF iron-making, BOF steel-making, and steel rolling. Secondary processes that vary from plant to plant include types of hot metal pretreatment, differing types of secondary metallurgy, and methods of reheating before the rolling or plate mills. The assumptions of our historical model are as follows:

- Byproduct gases such as coke oven gas (COG), blast furnace gas (BFG), and basic oxygen furnace gas (BOFG) were not utilized for power generation in 1988, and are thus released to the environment instead [29].
- Pellets, anthracite, oxygen blast air from an oxygen plant, or lime are not used in iron-making [32].
- Water is consumed at 210 m^3 per metric ton of crude steel; this is an estimate from 1998, due to a lack of data for 1988 [31].
- BOF slag is assumed to be 0.0085 t per metric ton of crude steel, due to lack of data for 1988 [33].
- Mill scale is not recycled into the sintering plant [34].
- The distributions of water flows throughout the plant are the same percentages as for the same process today, although the usage rates differ greatly [35].
- The flows from the lime plant, iron ore powder, and lime from the raw material stores to the sintering plant remain unchanged from present-day amounts.
- The co-location of industries that could benefit from the products or waste streams of this historical plant is outside of the historical system boundaries.
- Because the fuel use for steel manufacturing is largely represented by coal, a conversion of off-gases into coal equivalent is assumed.

The above assumptions were required mostly due to data scarcity regarding the CSI in the late 1980s. Where values had to be assumed (i.e., lime flows, emission amounts), conservative estimates were made to avoid distorting the model.

2.3.2. Current integrated steel manufacturing process

Since 1990, major gains in energy conservation came about in the CSI through structural adjustment and energy and material flow optimization. The CSI focused on waste heat recovery-and-reuse technology, raw material and fuel pretreatment technologies, plant layout optimization, energy management, and controls using automation technology [29].

The system boundaries of the current steel manufacturing process and the flows that cross this boundary throughout the system are defined in Fig. 6.

Throughout this study, the model assumes a structure similar to Fig. 6, in which byproduct gases are transported to boilers in the power plant to produce steam, which is then converted to electricity through turbines. Byproduct gases are also reused in the reheating furnace. This assumption is consistent with observations showing that in 2007, 90% of BFs larger than 1000 m^3 were equipped with a top gas pressure recovery turbine (TRT). By the end of 2004, nearly 25% of the CSI had coke dry quenching (CDQ) units installed and in operation [17,36]. In addition, by the end of 2006, 77% of key Chinese steel enterprises had installed BFG recovery equipment, and 64% had installed recovery equipment for other gases such as COG and BOFG [36]. The assumptions made for the current model are as follows:

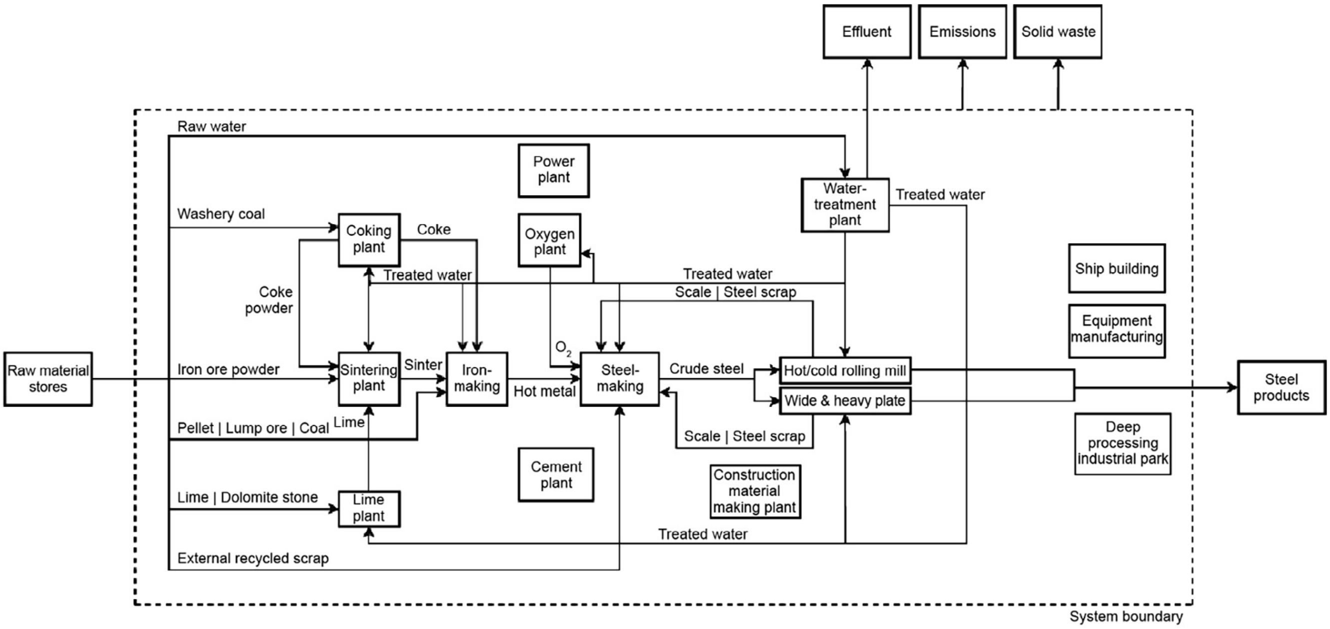


Fig. 5. Simplified historical integrated steel manufacturing process.

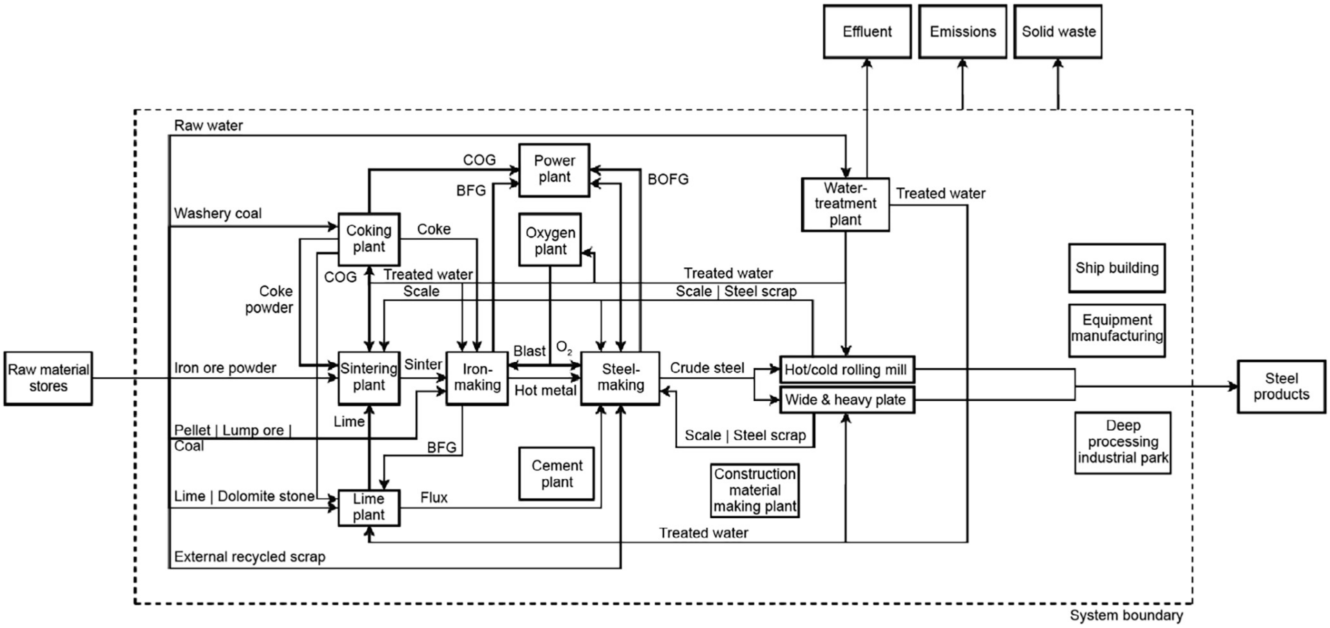


Fig. 6. Simplified current integrated steel manufacturing process.

- The co-location of industries that could benefit from the products or waste streams of this historical plant is outside of the historical system boundaries.
- Because the fuel use for steel manufacturing is largely represented by coal, a conversion of off-gases into coal equivalent is assumed.
- Generation irregularities of byproduct gases are assumed to be negligible, although in reality, uncertainty factors such as equipment maintenance could affect the stable production of gases.

2.3.3. Future developments in the integrated steel manufacturing process

Zhang and Wang [10] argued that a new type of development is needed to decrease the consumption of energy and resources through ecological reform. Current projects are underway in the CSI to substantiate these claims; these projects are exemplified by the Bayuquan eco-industrial park, which is being built by the Anshan Iron and Steel Group Corporation in addition to others. Although the Bayuquan eco-industrial park is currently under construction, its goal is to utilize the waste streams and products produced by the steel mill within the park, a process that was first introduced in practice by the Kalundborg eco-industrial park in Denmark [37]. This configuration is demonstrated in Fig. 7.

By better utilizing waste streams, the new configuration decreases the amount of waste generated by the industry by semi-closed cycling. In addition, other industries benefit from this configuration by coordinating geographic efficiency and sharing resources such as the onsite power plant. It is worthwhile to note

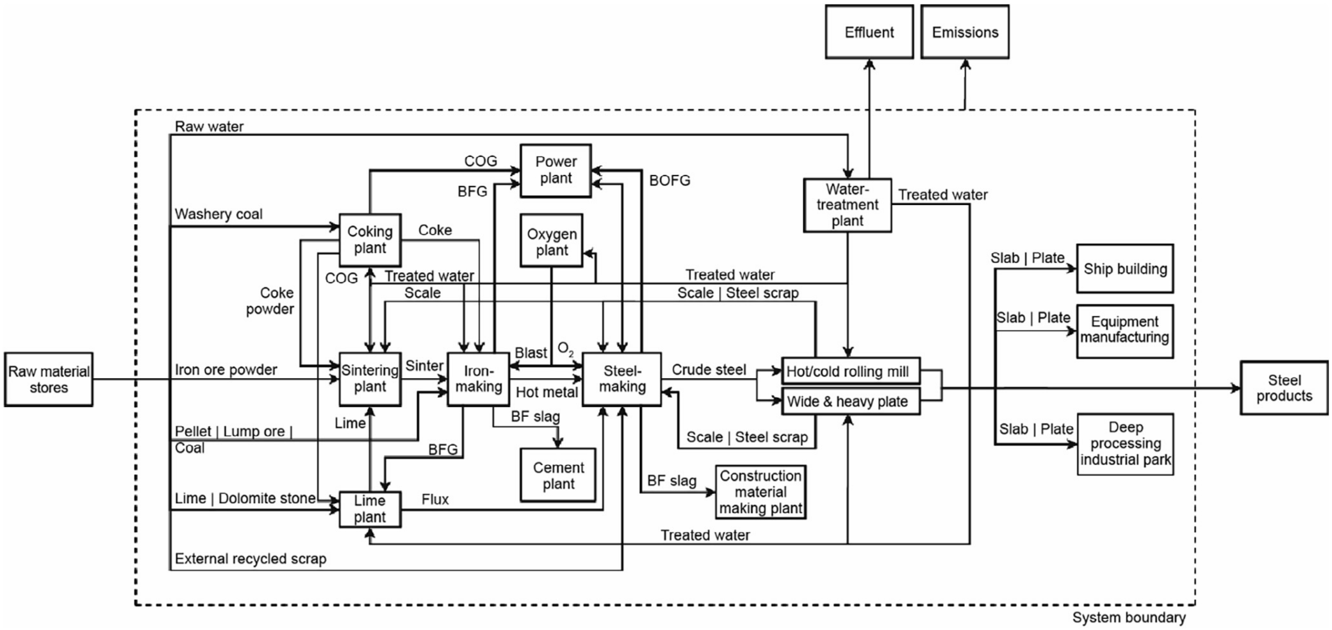


Fig. 7. Simplified future integrated steel manufacturing process.

that this configuration is solely based on current data; further research is needed to optimize the waste streams going to and from these industries in order to maximize production and minimize waste. Because our study focuses on the steel manufacturing process alone, we opted for the configuration shown in Fig. 7. The assumptions made for the future model are as follows:

- Future steel manufacturing will continue to use the BOF process.
- Because the fuel use for steel manufacturing is largely represented by coal, a conversion of off-gases into coal equivalent is assumed.
- Byproduct gases' irregularities in generation are assumed to be negligible, although in reality, uncertainty factors such as equipment maintenance could affect the stable production of gases.

3. Results and discussion

The results of the structure-based statistics from the ecological models are shown in Table 1.

When comparing the historical configuration shown in Fig. 5 with the current and future configurations in Figs. 6 and 7, one can observe the increase of $\lambda_{\max}$, which correlates to a higher potential for cyclicity within the overall structure. In the future configuration, the cyclicity decreases as more exports are sent from the system to sister industries. If material streams were introduced from these sister industries back into the steel manufacturing system, it is expected that $\lambda_{\max}$ would then be greater than the current configuration.

Greater pathway proliferation rates are expressed by our results from increasing G and decreasing V from historical to future configurations. Given the greater potential for cyclicity, connectance, and pathway proliferation in connections that is observable in the current and future configurations, it is apparent that the overall structure of the steel manufacturing process has improved over time and has become organized more like a natural system.

The results from the flow-based statistics are summarized in Table 2.

The results in Table 2 show that the system has improved substantially from the historical to current in terms of FCI, MPL, and AMI. The MPL changes show that the current configuration allows materials to "touch" more actors—that is, allows a greater complexity in flow—throughout the system before being exported. In the future configuration, the structure becomes more streamlined. Therefore, the future configuration demonstrates a need for higher cyclicity, as the MPL metric indicates that the resources used in the future network are not used to their full potential. This does not mean that the historical configuration was a better-performing structure; rather, it indicates that the future configuration has an unrealized potential for recycling that did not exist before, as demonstrated in the metric in Table 1. The FCI shows the activity throughout the system that is devoted to cyclicity, so these results suggest that a decreasing amount of total system activity is devoted to cyclicity. The FCI is a dimensionless number, as is the MPL, which accounts for the percentage of all fluxes generated by cyclicity, or the fraction of total activity in the system that is devoted to cyclicity. Furthermore, an increased AMI is indicative of increased system maturity and cyclicity within the system [1]. The TST_p complements these values, indicating an increase in process efficiency through its decreasing value. This decrease in TST_p is most likely due to the overall decrease in emissions within the steel industry. Our results also suggest an overall system increase in R, with a corresponding decrease in ASC/DC. Robustness indicates lower constraints on flows, which allow a system to maintain function when faced with perturbations. In contrast, the decrease in ASC/DC indicates lower constraints on flows resulting in less efficiency. Our analysis suggests that the progression of the CSI is indicative of a system that is increasing in redundancy, and that the changes in structure hold a potential for greater cyclicity that is not being utilized, thus decreasing efficiency. It has been observed that most ecological systems, particularly those that are deemed healthy by independent criteria, occupy a balance between efficiency and system redundancy or robustness. When ASC/DC is plotted against R, the peak demonstrates this balance. Layton et al. [4] combined economic resource networks, water networks using the data from Bodini et al. [26], economic networks using the data from Kharrazi et al. [38], and 93 natural ecosystems and plotted their results on this curve, as shown in Fig. 8. In Fig. 8, highly redundant systems such as the Kharrazi economic networks demonstrate high redundancy and low efficiencies, whereas highly efficient industries such as Bodini's Italian municipalities and the historical and current steel industry configurations reflect lower

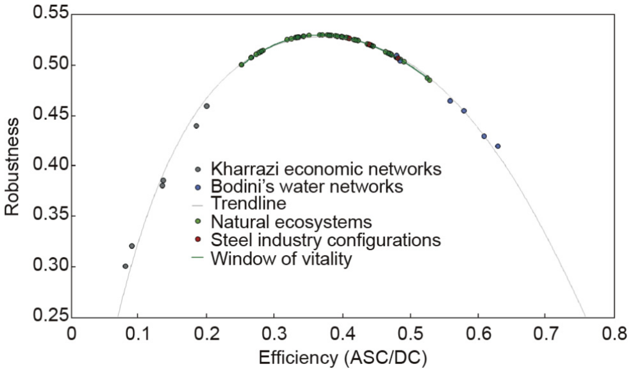


Fig. 8. Steel industry configurations on the robustness curve.

Table 1

Structure-based statistics for the historical, current, and future BOF steel manufacturing processes.

Structure-based statistics	$\lambda_{\max}$	L_D	P_R	G	V	N	L	n_{predator}	n_{prey}	C
Historical	1.4423	0.95	0.800	1.900	2.375	20	19	10	8	0.048
Current	2.1551	1.70	1.000	2.615	2.615	20	34	13	13	0.085
Future	2.1112	1.90	1.385	2.923	2.111	20	38	13	18	0.095

Table 2

Flow-based statistics for the historical, current, and future BOF steel manufacturing processes.

Flow-based statistics	FCI	MPL	AMI	ASC	DC	TSO	TST_P	ASC/DC	R
Historical	0.716	7.212	1.922	425.561	782.050	356.488	194.375	0.5442	0.4777
Current	0.736	11.412	2.053	173.356	321.066	147.709	77.664	0.5399	0.4801
Future	0.277	3.773	2.122	53.941	115.319	61.378	18.596	0.4678	0.5127

robustness but higher efficiencies. Our analysis adds to that of Layton et al. [4] by demonstrating the progression of steel manufacturing over time.

The future configuration of the CSI is the only configuration that observes a healthy balance of redundancy and efficiency. Ulanowicz et al. [39] termed the peak inhabited by natural ecosystems as the "window of vitality." As demonstrated by our results in Tables 1 and 2 and Fig. 8, the steel industry is moving toward the balance that is inhabited by natural ecosystems. However, our results also suggest that the future of steel manufacturing has the potential to improve further. The incorporation of the steel manufacturing industry with sister industries could be configured, as demonstrated in Fig. 7. These industries may share resources or waste streams, which has been shown to further reduce waste and the consumption of resources while still mimicking the balance between redundancy and efficiency that is held by natural ecosystems.

These results suggest that understanding how industrial ecosystems interact can aid in the future design, development, and operation of sustainable industrial systems. We suggest that cooperative industries that are coupled in order to maximize an efficient use of resources while minimizing waste are examples of designs that could further improve the overall sustainability of the CSI with respect to ecological indicators. However, future work is needed to demonstrate how changes in material efficiencies in industrial processes translate to ecosystem statistics such as the ones used throughout this study. The translation of industrial performance and its relation to ecosystem metrics are not well understood, leading to a lack of understanding on how these metrics could be utilized as performance indicators outside of natural systems.

4. Conclusion

Through an ecological analysis of material flows in the steel manufacturing industry in the past and into the future, our analysis suggests that the Chinese steel manufacturing industry using BOF process is traversing a sustainable path forward. Our analysis indicated a high waste of material resources and low cyclicity of materials within the Chinese steel manufacturing process during the 1980s. During the past three decades, however, great efforts have been made throughout the industry to incorporate new technology, policies, and optimization. The current results of the steel manufacturing process suggest a more cyclical network and greater efficiency among individual processes, as well as a higher level of "ecosystem" maturity. The results of our analysis of future industry plans show that through partnership with sister industries, further improvements can be accomplished to balance the efficiency and robustness of the system while simultaneously reducing waste. Furthermore, through an investigation of the balance of efficiency versus robustness, our analysis shows that the steel manufacturing industry can continue to improve while strengthening interactions that more closely resemble natural ecosystems. We suggest that future studies delve further into the possible material and energy flows that can exist between industries in order to facilitate meaningful decision support for the creation and reorganization of industrial systems; we also suggest that further work be undertaken to understand how an ecological understanding of natural systems translates to industrial performance.

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Compliance with ethics guidelines

Stephen M. Malone, Marc J. Weissburg, and Bert Bras declare that they have no conflict of interest or financial conflicts to disclose.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.eng.2018.03.008.

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