ENVIRONMENTALLY FRIENDLY SCHEDULING OF PRIMARY STEELMAKING PROCESSES

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Abstract

The scheduling problem in steel plants has been recognized as one of the most difficult industrial scheduling problems. Moreover, the steel industry is also known to be a highly environment-intensive industry. In order to deal with two problems simultaneously, we present a multiobjective short-term scheduling model for the operation in primary steelmaking processes. The objectives of the proposed multiobjective MILP model are to maximize the total profit and to minimize the environmental impacts relevant to the steelmaking processes. The optimization result shows a trade-off between environmental and economic aspects and the decision maker can select any solution among the Pareto solutions considering these aspects simultaneously.

Keywords

Steelmaking processes, Environmental impacts, LCA, Multiobjective optimization, Scheduling

Introduction

For given resources over a short-term or long-term horizon, the individual company can maximize the total profit by efficient algorithms for production planning and operation scheduling. At the same time, environmental impacts should be considered in the scheduling problem because unit equipment or manufacturing facilities are known to be potential candidates for waste generation (Grau *et al*., 1996; Stefanis *et al*., 1997). Therefore, an efficient and environmentally friendly scheduling procedure must be taken into account for a decision-making (Song *et al*., 2002).

In particular, steel plants have a complicated manufacturing environment with various batch and continuous modes, which can be recognized as one of the most difficult industrial scheduling problems (Lee *et al*., 1996; Moon and Hrymak, 1999). Moreover, the steel industry is a highly environment-intensive industry discharging various kinds of emissions. Thus, to deal with two problems simultaneously, a systematic methodology for the environmentally friendly scheduling of the steelmaking processes is presented in this study. The methodology is largely based on the framework by Stefanis *et al*. (1997) and Azapagic and Clift (1999). First, the process scheduling model consists of two parts: economic model and environmental model employing life cycle assessment (LCA). Then, these two models are incorporated into the multiobjective optimization (MO) framework. In the next section, the methodology for the environmentally friendly scheduling will be presented, followed by a case study application to a steelmaking process.

Methodology for the Environmentally Friendly Scheduling

Overall framework of the methodology for the environmentally friendly scheduling mainly consists of three steps as shown in Figure 1. First, the environmental and economic models are constructed with the LCA and scheduling algorithm, respectively. Then, these two models are incorporated into the MO framework to consider them simultaneously. Finally, a decision maker can select a proper scheduling solution obtained from the MO problem.

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Figure 1 shows the methodological framework for the environmentally friendly scheduling.

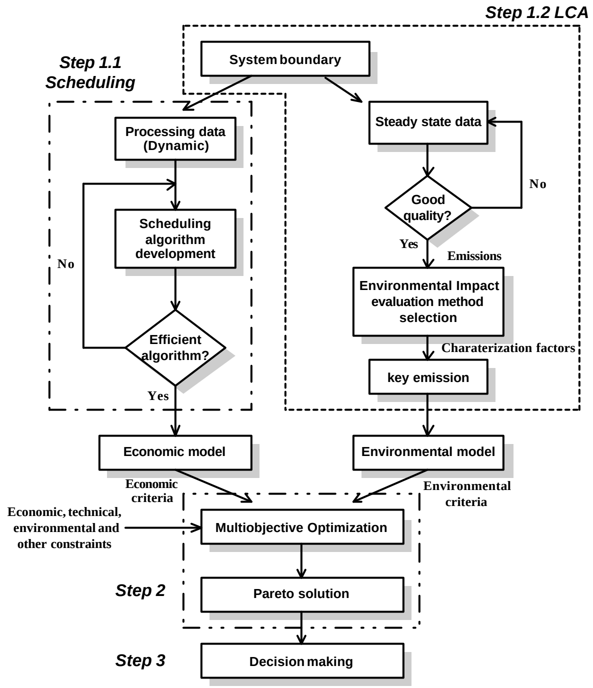

Figure 1. The methodological framework for the environmentally friendly scheduling

Step 1.1: Construction of the scheduling model

In this step, an efficient scheduling model for the steelmaking processes is developed. The objective of the scheduling model is to maximize the total profit or minimize the makespan.

Step 1.2: Construction of the environmental model by the LCA study

According to the LCA methodology (ISO, 1997), all material and energy inputs into the system boundary are traced back to their extraction from the earth, and all emissions associated with these inputs into the system's environment are quantified. Then, life cycle inventory (LCI) data collected during the above procedure is used to evaluate environmental impacts by classification and characterization stages in LCA. Finally, key emissions, which contribute significantly to the environmental impacts, are identified and then considered as parameters and variables in the environmental model in the next step.

Step 2: Formulation of the multiobjective MILP model

The general multiobjective MILP model, which involves continuous and discrete variables, can be obtained by combining the economic and environmental models as follows:

$$\min\ f(x,y) = [f_1, f_2, \ldots, f_m]$$

$$\text{s.t.} \quad h(x,y) = 0 \qquad (P)$$

$$g(x,y) \le 0$$

$$x \in X,\ y \in Y = \{0,1\}^r$$

where x and y denote the vectors of q continuous and r integer (discrete) variables, and objective functions f and all the constraints are linear functions of the design variables. Equality constraints, $h(x,y)=0$ and inequality constraints, $g(x,y)\le 0$ are dictated by the physical processes and resource limitations.

In this step, ε-constraint method (Cohon, 1978) is employed to generate the Pareto solutions of the MO problem (P). From the results, Pareto solutions representing the trade-off between economic and environmental aspects can be obtained.

Step 3: Decision making

Finally, the decision maker can select any schedule among the Pareto solutions obtained in step 2 according to his or her preference.

Application to Primary Steelmaking Processes

The motivating example presented in our previous work (Moon *et al.*, 2000) is revisited as a case study to demonstrate the proposed methodology.

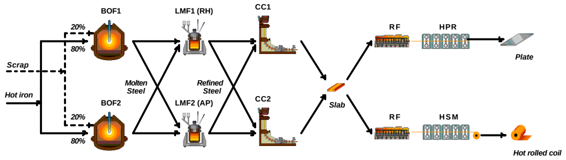

Figure 2. Primary steelmaking process for a case study

Figure 2 shows the case study that a primary steelmaking process consists of two basic oxygen furnaces (BOF), two ladle metallurgical facilities (LMF) (RH and AP types), two continuous casters (CC), a heavy plate rolling (HPR), and a hot strip mill (HSM). For more detail operation condition including process data, see the reference (Moon *et al.*, 2000).

Step 1.1: Construction of the scheduling model

The MILP model for short-term scheduling of the primary steelmaking process is developed based on a novel continuous time formulation (Moon *et al.*, 2000).

Step 1.2: LCA study

From the results of LCI for the steelmaking processes, the 7 air emissions and 16 water emissions were identified as emissions inventory. 6 air emissions (SO_x, NO_x, CO, CO_2, Dust, and Zn) and 4 water emissions (Ni, Cd, Pb, and As) are selected as the key emissions to develop the environmental model since other emissions have been found to have less effects on environment via the screening LCA. Figure 3 shows the relative contribution of the different processes to selected emissions and environmental impacts. As shown in this Figure, it was found that a sintering process has the most significant contribution to Cd, CO, NO_x, SO_2, and dust emissions to air. The key emissions data will be used as parameters in the environmental model later.

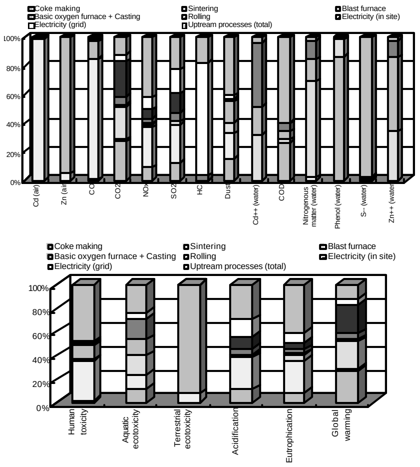

Figure 3. The relative contribution of the steelmaking processes to selected emissions and environmental impacts

Step 2: Multiobjective MILP model

On the basis of the notation and constraints presented in the scheduling model, a multiobjective MILP model for the environmentally friendly scheduling involves the following additional constraints:

$$\sum_{i\in I}\sum_{k\in K}\left(\sum_{j\in J_i} Va_{ikj}\,W_{ijl} + Vy_{i,\text{plate},k}\,W_{i,\text{HPR},l} + Vy_{i,\text{coil},k}\,W_{i,\text{HSM},l}\right) \le b_l \quad (1)$$

where W_{ijl} is the amount of emission l for product i at unit j and this emission inventory data for the case study are obtained from the LCI results in step 1.2. Eq. (1) expresses that total amount of waste for emission l is constrained by environmental regulation limits for emission l, b_l.

In the scheduling of a primary steelmaking process considering environmental impacts, two objectives can be described: maximizing the profit and minimizing the environmental impacts.

Objective 1: Maximization of Profit, *PR*

$$PR = \sum_{i\in I}\sum_{s\in S_i}\sum_{k\in K} Vy_{isk}\ PRICE_{is} - \sum_{i\in I}\sum_{k\in K}\sum_{j\in J_i-\{\text{HPR},\text{HSM}\}} Va_{ikj}\,OC_{ij} - \sum_{i\in I}\sum_{k\in K}\sum_{s\in S_i}\sum_{j=\{\text{HPR},\text{HSM}\}} Vy_{isk}\,OC_{ij} \quad (2)$$

The shapes *s*, slabs, plates, and coils, of product *i* are considered as the final product to be delivered to customer. The first term of Eq. (2) denotes the total sale price on the market and the other two terms are total operating costs.

Objective 2: Minimization of Environmental Impacts, *EI*

$$EI_m = \sum_{l\in L}\sum_{i\in I}\sum_{k\in K} CTF_{ml}\left(\sum_{j\in J_i} Va_{ikj}\,W_{ijl} + Vy_{i,\text{plate},k}\,W_{i,\text{HPR},l} + Vy_{i,\text{coil},k}\,W_{i,\text{HSM},l}\right) \quad \forall\ m\in M \quad (3)$$

where EI_m denotes the environmental impact criterion m such as Human toxicity, Ecotoxicity, etc. CTF_{ml} is the characterization factor for emission l in a given impact category m from CST 95 criteria (Jolliet and Crettaz, 1997). In this study, the human toxicity potential (*HTP*) is selected as the environmental impact criterion. The reference substance for human toxicity is arbitrarily chosen as the effect of inhalation of lead emitted to the air (Pb-air).

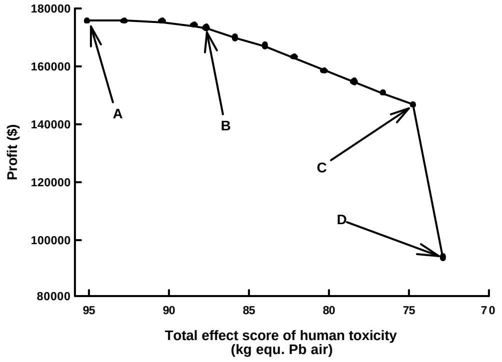

Figure 4. Pareto curve for the case study

The ε-constraint method was used in this work to generate the set of Pareto solutions of the problem. The economic profit *PR* (Eq. (2)) is selected as the primary objective function and is optimized while the other objective function *EI* is converted into constraints in (P). And then the problem can be solved for multiple ε-values to generate Pareto solutions with the scheduling and environmental models. Figure 4 demonstrates Pareto curve for the case of two objectives, maximization of profit and minimization of human toxicity, when the horizon time is 34,000 sec (9.44 hours). Points A and D in this figure show the maximized profit and the minimized *EI*, respectively.

Step 3: Decision making

Among the Pareto solutions shown in Figure 4, a proper solution can be selected according to the decision maker's preference. In order to investigate the difference between optimum points within the Pareto set, two points, A and B in Figure 4 are compared. If the decision maker prefers to operate the process profitably rather than environmentally friendly, a schedule with the maximum profit ($175,476), corresponding to point A, may be selected. However, point B is much better than A in terms of human toxicity because the environmental performance improvement by 33.3 % (from 95.13 to 87.68) is relatively higher than the profit decrease by 2.9% (from \$175,475 to \$172,947) in Figure 4.

To take a deeper look at the points, the total effect score of human toxicity corresponding to points A to D are summarized in Table 1. The table shows that SO_x has the greatest contribution to the HTP and also air emission Zn contributes significantly to the total effect score of human toxicity. Note that the difference of EI_{HTP} by Zn ($EI_{HTP,Zn}$) is larger than the EI_{HTP} by SO_x ($EI_{HTP,SOx}$) when points A and B are compared. It means that the most reduction of EI_{HTP} from A to B has been achieved by the reduction of Zn in air emission although SO_x has the greatest contribution to the total effect score of human toxicity. This is due to the fact that most of the Zn emission as one of the main key burdens for HTP is generated within a scheduling system boundary including BOF and CC while just 6.5% of total SO_x emission is produced during the operation (see Figure 3). Table 2 shows batch amounts at each unit corresponding to points A and B. The results of point A in Table 2 are based on the economic consideration only. However, when the environmental effect is simultaneously considered with the economic effect in point B, the operations of two equipments (BOF2 and CC2) are controlled to satisfy the environmental regulation, because the environmental performances of BOF1 and CC1 are better than those of BOF2 and CC2.

Table 1. Total effect score of human toxicity corresponding to points A to D in Figure 4

	EI_{HTP}	Air emissions				
		$EI_{HTP,CO}$	$EI_{HTP,Nox}$	$EI_{HTP,SOx}$	$EI_{HTP,Dust}$	$EI_{HTP,Zn}$
A	**95.13**	9.42	7.10	39.20	11.14	28.25
B	**87.68**	9.10	6.96	38.55	10.79	22.25
C	**74.65**	7.72	5.91	32.68	9.16	19.14
D	**72.78**	7.61	5.77	31.51	9.00	18.87

Table 2. Batch amount at each unit corresponding to points A and B in Figure 4

		Equipment							
Point	Slot	BOF1	BOF2	LMF1	LMF2	CC1	CC2	HPR	HSM
A	1	300	-	300	-	300	-	120	150
	2	-	315	-	315	-	315	126	158
	3	374	-	374	-	-	374	149	187
	4	-	400	-	400	-	400	160	200
	5	-	400	-	400	-	400	160	200
	6	400	-	400	-	-	400	160	200
Total		**1074**	**1115**	**1074**	**1115**	**300**	**1889**	**875**	**1095**
B	1	322	-	-	322	322	-	129	161
	2	-	300	300	-	-	300	120	150
	3	366	-	366	-	366	-	147	183
	4	366	-	366	-	366	-	147	183
	5	400	-	-	400	400	-	160	200
	6	400	-	-	400	400	-	160	200
Total		**1854**	**300**	**1032**	**1122**	**1854**	**300**	**863**	**1077**

Conclusions

In this study, a systematic methodology for scheduling of steelmaking processes considering environmental impacts is presented. Through LCA, environmental burdens and impacts for steelmaking processes are identified and quantified, and the results make it possible to evaluate possibilities for improving its environmental performance in steelmaking processes. And then, the results are embedded in a multiobjective formulation in order to investigate the effect of environmental impacts on the scheduling of the processes. The analysis of optimization results shows that the environmental impacts of the process become large in proportion to profit and we need to select the operation schedule considering the environmental impacts which are regulated by the environmental policy of the company.

Acknowledgments

The authors would like to acknowledge the advice of Prof. O. Jolliet at Swiss Federal Institute of Technology Lausanne in the course of this work. This work was also partially supported by the Brain Korea 21 project and Center for Ultramicrochemical Process Systems sponsored by KOSEF.

References

Azapagic, A., Clift, R. (1999). The application of life cycle assessment to process optimization. *Computers Chem. Engng.*, *23*, 1509.

Cohon, J. L. (1978). *Multiobjective programming and planning*, Academic Press, NY.

Grau, R., Graells, M., Corominas, J., Espuna, A., Puigjaner, L. (1996). Global strategy for energy and waste analysis in scheduling and planning of multiproduct batch chemical processes. *Computers Chem. Engng.*, *20*, 853.

International Organizatino for Standardization. (1997). ISO 14040 - Environmental management – Life cycle assessment – Principles and framework. Geneva.

Jolliet, O., Crettaz, P. (1997). Critical Surface-Time 95, a life cycle assessment methodology including fate and exposure. Swiss Federal Institute of Soil and Water Management.

Lee, H. S., Murthy, S. S., Haider, S. W., Morse, D. V. (1996). Primary productin scheduling at steelmaking industries. *IBM J. Res. Develop.*, *40*, 231.

Moon, S., Hrymak, A. N. (1999). Scheduling of the batch annealing process – deterministic case. *Computers Chem. Engng.*, *23*, 1193.

Moon, S., Lee, D.-Y., Park, S. (2000). Mathematical model for scheduling of primary steelmaking processes. *In Proc. of the 4th Korea-France Workshop on Simulation, Optimization and Control in PSE.* Cheju, Korea, 123.

Song, J., Park, H., Lee, D.-Y., Park, S. (2002). Scheduling of actual size refinery processes considering environmental impacts with multiobjective optimization. *Ind. Eng. Chem. Res.*, *41*, 4794.

Stefanis, S. K., Livingston, A. G., Pistikopoulos, E. N. (1997). Environmental impact considerations in the optimal design and scheduling of batch processes. *Computers Chem. Engng.*, *21*, 1073.