" Steel consumption per capita is considered to be the index of relative national prosperity of a nation. The steel market has become highly competitive in the last few years due to a sudden growth in the Chinese economy. As a result, the highest priority is being accorded to producing steel at the lowest possible cost. The primary objective of latest research work on steel production is to identify the most efficient optimization technique to arrive at the least cost approach to produce a given quantity of steel in an integrated steel plant."

Steel Production at Optimal Cost

By A K Shukla, B Deo and K Deb

Introduction

The steel industry plays a vital role in the economic development of a nation. The prosperity of any nation can be judged by the total steel consumption in buildings/infrastructure, transportation, giant manufacturing industries, power generation plants, railways, automobiles, capital goods, etc. In fact, steel consumption per capita is considered to be the index of relative national prosperity.

The trend in world steel production is shown in Fig.1. The steel produced by different countries is shown in Table 1 on page 2. India ranks ninth in the world steel production. However, the Indian industry faces severe international competition. In particular, the steel market has become highly competitive in the last few years due to a sudden growth in the Chinese economy. As a result, the highest priority is being accorded to producing steel at the lowest possible cost.

In order to meet this challenge, considerable effort is being devoted in developing a better scientific understanding of the metallurgical processes. Similarly, mathematical models and advanced optimization techniques have been applied to reduce the cost of steel production while introducing new metallurgical processes and evaluating the impact of the operating parameters at each of the units on production. To this end the

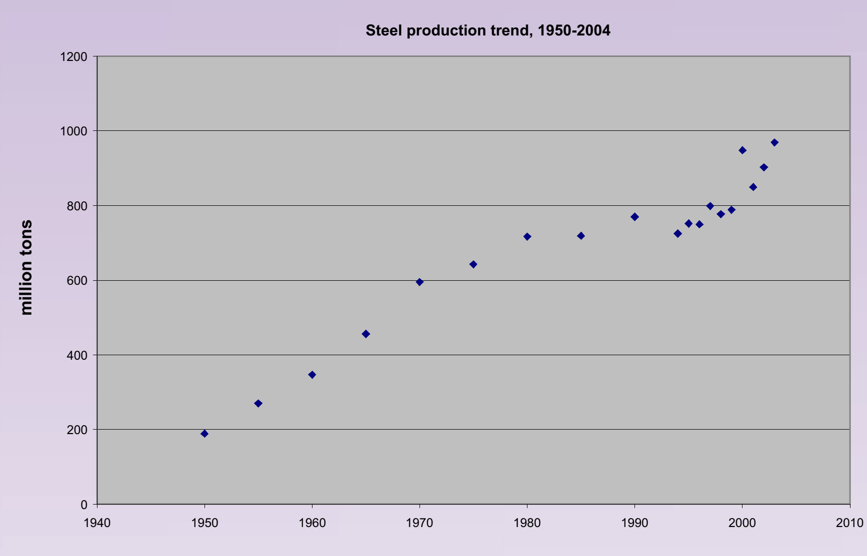

Fig. 1: Trend of world steel production, 1950-2004

Table 1 : Steel production in different countries during 2003 and 2004

Country	Rank in 2004	Production (mt, in 2004)	Rank in 2003	Production (mt, in 2003)
China	1	272.5	1	222.4
Japan	2	112.7	2	110.5
USA	3	98.9	3	93.7
Russia	4	65.6	4	61.5
S Korea	5	47.5	5	46.3
FR Germany	6	46.4	6	44.8
Ukraine	7	38.7	7	36.9
Brazil	8	32.9	9	31.1
India	9	32.6	8	31.8
Italy	10	28.4	10	26.8
France	11	20.8	11	19.8
Turkey	12	20.5	13	18.3
Taiwan	13	19.5	12	18.8
Spain	14	17.7	14	16.5
Mexico	15	16.7	16	15.2
Canada	16	16.3	15	15.9
UK	17	13.8	17	13.3
Belgium	18	11.7	18	11.1
Poland	19	10.6	20	9.1
S Africa	20	8.7	21	7.9
Iran	21	8.7	21	7.9
Austria	22	7.4	22	7.5
Czech Republic	23	7.0	23	6.8
Netherlands	24	6.8	24	6.6
Austria	25	6.5	25	6.3
Romania	26	6.0	27	5.7
Sweden	27	6.0	26	5.7
Kazakhstan	28	5.4	29	4.9
Argentina	29	5.1	28	5.0
Finland	30	4.8	30	4.8
Egypt	31	4.8	32	4.4
Venezuela	32	4.6	35	3.9
Thailand	33	4.5	36	3.6
Slovakia	34	4.5	31	4.6
Malaysia	35	4.0	33	4.0
S Africa	36	3.9	34	3.9
Indonesia	37	2.8	39	2.0
Luxemburg	38	2.7	37	2.7
Bulgaria	39	2.4	3.8	2.3
Greece	40	2.0	41	1.7
Hungary	41	2.0	40	2.0
Others		21.4		19.7
Total World Production		1056.7		969.3

mathematical relationships between inputs and outputs have to be established first. Besides, the constraints on the operating practices and the costs of adopting alternative practices must be kept in perspective. Fig. 2 represents a typical configuration of a BOF (basic oxygen furnace)-EAF (electric arc furnace) based integrated steel plant.

The primary objective of this paper is to identify the most efficient optimization technique to arrive at the least cost approach to produce a given quantity of steel in an integrated steel plant.

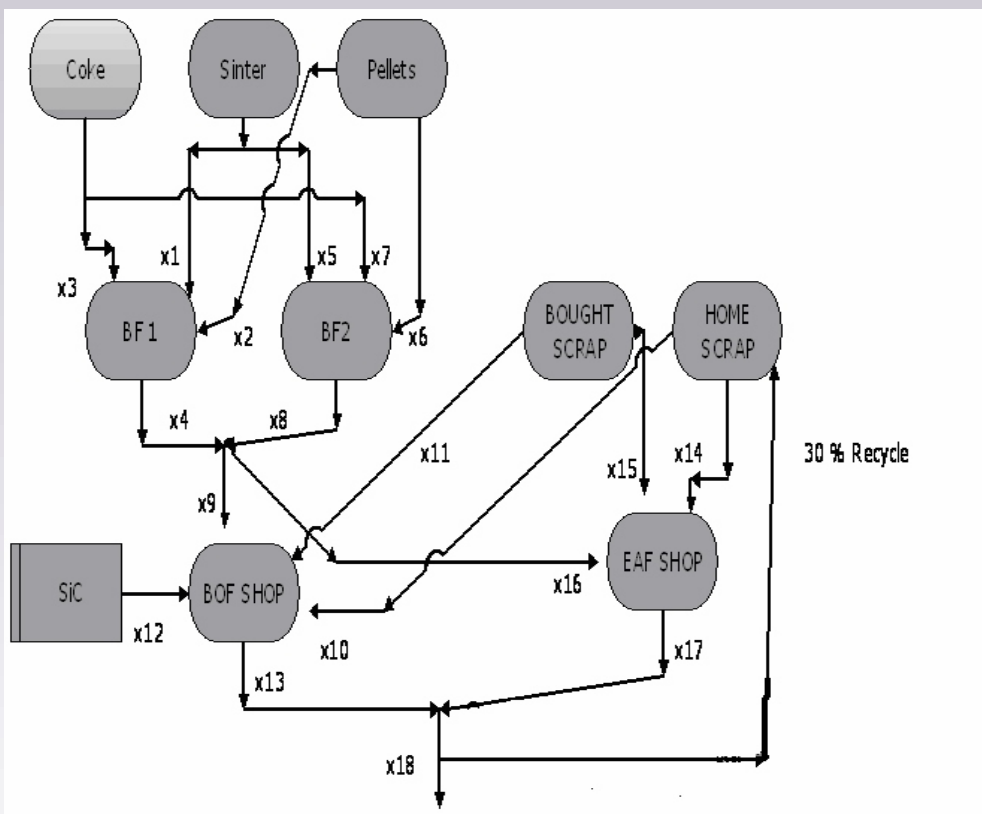

Fig. 2: Schematic layout and material flow in the primary end of an integrated steel plant

Process Description of an Integrated Steel Plant

The primary end of the process layout in Fig. 2 consists of a sinter plant, a palletizing plant, coke ovens, blast furnaces (BFs), Oxygen Steelmaking Furnaces (BOF), and Electric Arc Furnaces (EAF). The input rate of raw material at any processing stage depends upon their composition, cost and production rate. The BOF and EAF are capable of consuming scrap. The ratio of scrap to hot metal in BOF may be enhanced by adding an external fuel like SiC (silicon carbide). EAF may consume scrap in any proportion even upto 100%. The scrap consumed in the BOF and EAF may be either home scrap (produced within the works) or bought scrap. Different steel plants may have various combinations of these units and flow of materials. The objective is to find the optimum flow of materials in the supply chain subject to the operating constraints and quantitative relationships between the operating variables. If cost calculations are carried out for a type of layout and material flow as depicted in Fig. 2, with all constraints at each processing unit and added up, we may end up with a cost function having 20 to 25 variables with 30 to 40 linear or nonlinear constraints. It is a very challenging task to solve this type of optimization problem. It therefore requires evolutionary methods like GAS to be applied. In this article the solution is obtained by various classical methods like SQP, ASM, and an evolutionary method like GAS. The results have been compared in order to select the most suitable one.

Problem Description

The optimization problem discussed in this work relates to the minimization of the total cost of production for the entire chain of production units in the primary end of the steel plant. It consists of 25 variables with 35 constraints including both linear and non-linear equations. The optimization techniques applied to minimize the overall cost are LP-GP (Linear Programming and Gradient Projection), Sequential Quadratic Programming (SQP), Annealed Simplex method (ASM), and Genetic Adaptive Search (GAS) [1-10]. The operating constraints and relationships between various feed rates are as follows.

Blast Furnace I

Operating range: 0.7 to 1.6 million tons per annum
Production relationship: 1 ton hot metal requires 1.4 tons of sinter; 1 ton hot metal requires 1.1 tons of pellets
Maximum capacity with sinter: 1.2 million tons per annum

Blast Furnace II

Operating range: 0.4 to 0.8 million tons per annum
Production relationship: same as blast furnace one
Maximum capacity with sinter: 0.6 million tons per annum
The coke rate for both blast furnaces is defined as an empirical relationship in terms of input and output feeds.

Basic Oxygen Furnace

Maximum capacity: 3.5 million tons per annum
Yield : 90%
Maximum scrap ratio: 0, 25

Each ton of SiC allows additional 12 tons of scrap.
The maximum amount of SiC that may be charged is 1/24 of the hot metal charge.

Electric Arc Furnace

Maximum Capacity 1.5 million tons/annum with 100 % scrap
: 2.0 million tons/annum with 100 % hot metal

Iron Yield : 92%

Objective function

The objective function selected for optimization is the total annual cost of production of crude steel

Cost=F1+F2+F3+F4+c1.x1+c2.x2+c3.x3+c4.x4+c1.x5 +c2.x6 +c3.x7+c4.x8+c11.x11+c11.x15+c12.x12 +C13.x13 +c10.x10+c10.x14+c17.x17

Where c1 to c17 are in units per ton and F1 to F4 are the annual fixed costs. The values used in this study are

c1=1.40	c11=0	F1=480000
c2=2.00	c12=12.00	F2=330000
c3=1.67	c13=1.00	F3=700000
c4=0	c10=0	F4=200000
c8=0	c17=1.73	

The overall problem consists of 10 equality constraints and 25 inequality constraints, summarized in Table 2 on page 5. The problem has been solved by using various classical methods like SQP, ASM and an evolutionary method like GAS and compared with the solutions obtained by LP-GP method. A comparison of results from all methods is given in the Table 3 on page 6.

Table 2 : Constraints for the optimization problem of steel plant

Constraint No.	Description
1	x4-0.715x1-0.91x2=0
2	x3-R1x4=0
3	x8-0.715x5-0.91x6=0
4	x7-R2.x8=0
5	x13-0.90x9-0.90(x10+x11)=0
6	x17-0.92(x14+x15+x16)=0
7	x10+x14-0.3x18=0
8	x18-x17-x13=0
9	x4+x8-x9-x16=0
10	x18-4.286=0
11	x9-4.0(x10+x11-12x12)>=0
12	x12-24.0x9 <=0
13	2.0-(x16+1.33(x14+x15))>=0
14	x1-1.7<=0
15	x4-1.6<=0
16	x5-0.84<=0
17	x8-0.8<=0
18	x13-3.5<=0
19	x4-0.7>=0
20	x8-0.4>=0
21-35	xi >= 0 (where i = 1 to 3,5 to 7,9 to 17)

Optimization by Sequential Quadratic Programming (SQP)

This method belongs to the class of optimization techniques which are based upon quadratic approximation to the design space. This program generates constrained second order search directions by solving a quadratic programming sub-program at each iteration. The first step of an optimization problem using SQP is to assign initial guess values to all design variables, the penalty parameter, R, a user defined constraint γ, a parameter specifying the extent of gradient descent search ($0 \le \gamma \le 1$), a permissible constraint violation parameter ε_1, and a tolerance for convergence check ε_2. The parameter ε_1 allows the extent of constraint violation beyond which the solution is considered infeasible. The parameter ε_2 is used to control the termination of the optimization procedure. Initially guess values were used to solve the problem. All values (x1-----x18) were set to be 1.4, R was assumed to be 1.0, γ assumed to be 0.20 and ε_1 and ε_2 were assumed to be 0.001. The values of (x1----x18) at the optimum point are evaluated and listed in Table 3 on page 6. However, the scrap values are not in agreement with the heat and mass balance of the BOF process. Hence, this problem is further solved by adding one more constraint that scrap charged in BOF cannot be more than 30% of the output steel. The calculations are performed for different guess values as shown below, and results are again compared.

Case - I: All guess = 0.0005
Case - II: All guess = 0.05
Case - III: All guess values = 1.0

In all these cases other SQP parameters were kept constant, viz., R =1.0, γ =0.2, $\varepsilon_1=\varepsilon_2$=0.001. The results from different guess values are the same except that the number of iterations is different in each case.

Optimization by Annealed Simplex Method

Table 3 : Final solution obtained by different techniques

Parameters	LP-GP	SQP	SQP-1	SQP-2	SQP-3	ASM	GAS
BF-1							
Coke	0.804	0.439	0.770	0.770	0.770	0.831	0.712
Sinter	1.700	0.979	0.271	0.271	0.271	0.488	0.276
Pellets	0.000	0.000	1.494	1.494	1.494	1.348	1.482
Hot Metal Output	1.215	0.700	1.553	1.553	1.553	1.576	1.545
BF2							
Coke	0.274	0.281	0.428	0.428	0.428	0.441	0.395
Sinter	0.564	0.559	0.136	0.137	0.138	0.214	0.115
Pellets	0.000	0.000	0.770	0.772	0.771	0.749	0.645
Hot Metal Output	0.403	0.400	0.800	0.800	0.800	0.801	0.765
BOF							
SiC	0.100	0.154	0.023	0.023	0.023	0.042	0.039
Bought Scrap	1.605	1.326	0.386	0.386	0.386	0.217	0.260
Home Scrap	0.000	0.798	0.484	0.484	0.484	0.688	0.645
Hot Metal	1.618	1.100	2.350	2.350	2.350	2.383	2.306
Steel Output	2.902	2.900	2.901	2.901	2.901	2.950	2.890
EAF							
Bought Scrap	0.218	1.016	0.702	0.703	0.703	0.827	0.872
Home Scrap	1.285	0.488	0.801	0.801	0.801	0.626	0.641
Hot Metal	0.000	0.000	0.000	0.000	0.000	0.000	0.003
Steel Output	1.383	1.384	1.384	1.384	1.384	1.333	1.395
Total Hot Metal	1.618	1.100	2.354	2.354	2.353	2.383	2.310
Total Steel	4.285	4.285	4.285	4.285	4.285	4.283	4.285
Total home scrap	1.285	1.285	1.285	1.285	1.285	1.294	1.286
Total Bought Scrap	1.823	2.342	1.088	1.088	1.089	1.044	1.133
Coke Rate BF- I	0.614	0.627	0.496	0.496	0.496	0.527	0.496
Coke Rate BF - II	0.703	0.704	0.535	0.535	0.535	0.549	0.528
Unit Cost (per ton of steel)	3.076	2.851	3.359	3.359	3.359	3.430	3.299
Relative cost	0.932	0.864	1.018	1.018	1.018	1.040	1.000
Function evaluation		374	6121	1163	1050	122,488	20000

This procedure is applicable only to the unconstrained optimization problems. In this approach, a combination of simulated annealing and Nelder and Meade's simplex search method is used. The simplex search method begins with a set of initial random solutions (called a simplex). The worst solution in the simplex is replaced by a new one, using a set of rules of expansion and contraction of the original simplex. The extent of expansion and contraction is governed by three parameters, namely α, β, and γ. The new solution created by using expansion or contraction rules is accepted or rejected based on the Metropolis algorithm used in the simulated annealing method. This problem of optimization consists of 18 variables with 35 constraints and one more additional constraint of limitation of scrap consumption in BOF within certain value. Since the problem to be solved has constraints, the penalty function method is used to transform the constrained optimization problem into an unconstrained optimization problem. The optimization calculations are carried out for $\alpha = 1$, $\beta = 0.5$ and $\gamma = 2$, and results are listed in Table 3 on page 6.

Optimization with GAS

This method is based upon the principle of natural evolution, where the solution in the solution domain is searched by procedures that use the mechanics of natural selection and natural genetics. The coding of each variable is done using binary strings. The objective function is evaluated for each string in the population. Once the objective function value is evaluated, the fitness and average objective function values are calculated. The difference between the average and minimum objective function has been evaluated and if this difference is very small, the GAS is terminated and it is assumed that optimum solution (global minimum) has been achieved. At this stage it means that all strings in the population are identical since the average value and optimum values are the same. If this criterion is not satisfied then a new set of strings is obtained with the help of genetic operators. The GAS operators chosen in the present optimization problem are

Population size	:	200
Total string length	:	100
Number of Generations	:	350
Cross Over Probability	:	0.60 to 0.80
Mutation Probability	:	0.01

Comparison of all the Solutions

- In comparison with SQP (unit cost 3.359 units/ton) and ASM (unit cost 3.430 units/ton), the lowest cost solution is obtained with GAS (unit cost 3.299 units per ton). The solutions obtained by SQP and ASM are 1.8 and 4 % worse than GAS solution. The reason behind obtaining the best solution using GAS is that it evaluates a number of solutions (a population) in each iteration.
- GAS techniques have unique search operator (crossover operator) and they are a better approach for searching the optimum solution. It is possible to achieve the global or near global optimal solution in complex, nonlinear and multivariable problems, using GAS.
- Although SQP method required smaller number of evaluations compared to GAS and ASM, the solution obtained by GAS is better than other methods. The SQP method is ideally suitable for solving quadratic functions. It is not suitable for problems having a large number of nonlinear constraints.
- GAS is more efficient and powerful than the other methods due to its unique population approach and inherent coding aspects.
- In practice, many new grades of steel may be produced to cater to different market segments. Such extensions can be handled by GAS methods though they complicate the specification and computation.
- It should also be noted that this paper emphasized production cost alone. Other policies like tariffs on imports and administered prices affect the costs of production. Essentially, some modifications of the parameter values assumed in this study can

account for such additional features.

On the whole, efficient production, using appropriate process controls, is a precondition to ensure economical production of steel.

References

- B Deo, K Deb, S Jha, V Sudhakar: ISIJ International, Vol 38 (1998).
- W.H Ray and J Szekely: Process Optimization, Wiley, New York (1973).
- J. S. Arora: Introduction to Optimum Design, McGraw-Hill, New York (1989).
- W. H. Press, S. A. Teukolsky, W. T. Vellering and B.P.G. Flannery : Numerical Recipes, 2nd Ed., Cambridge Univ. Press, Delhi (1992)
- G. A. Gabriele and T. J. Beltrachi: J. Mechanisms, Transmissions and Automation in Design, Trans. ASME, 109 (1987), No. 6, 248.
- O. K. Lim and J. S. Arora: Int. J. Numerical Methods in Eng., 24 (1984), No. 10, 1827.
- K. Deb: Optimisation for Engineering and Design, Prentice Hall ofIndia, New Delhi (1995).
- J. H. Holland: Adaptation in Natural and Artificial Systems, MIT Press, Ann Arbor (1975).
- D. E. Goldberg: Genetic Algorithms in Search Optimization and Machine Learning, Addison-Wesley, Reading, MA (1989).
- T. Russo, T. Miller: Iron and Steel Technology, November 2005.

About the author : Dr. Brahma Deo is a Professor in the Department of Materials and Metallurgical Engineering at IIT Kanpur, INDIA. He received his D.Phil. degree in Met. Engg. from the University of Burdwan. His Research Interests are Process Control and Modelling of BOF, AOD, VOD. Blast Furnace, Ladle Management ,FEM, ANN, GAS and process optimization in iron and steel-making.

About the author : Dr Kalyanmoy Deb is a Ph.D in Engineering Mechanics from the University of Alabama (Tuscaloosa)) and is a Professor of Mechanical Engineering at Indian Institute of Technology Kanpur, India. Prof. Deb has been honoured with the prestigious Shanti Swarup Bhatnagar prize in Engineering Sciences for the year 2005. His research interests primarily include Multi-Objective Evolutionary Algorithms, Real-Parameter Genetic Algorithms and Constrained Nonlinear Optimization. Other areas of interests are convergence analysis, population sizing, linkage issues leading to representation-operator interactions, test problem design, Hybrid Optimization Algorithms, Robotics and Artificial Intelligence Techniques.

About the author : Ajay Kumar Shukla is pursuing his M.Tech degree in the Department of Materials and Metallurgical Engineering at IIT Kanpur, India. He received his B.Tech Degree in Metallurgical Engineering from IIT Kanpur. His research interests include Process Automation and Control and Optimization of Steelmaking Processes using latest techniques involving Mathematical Models. Before joining the M. Tech programme at IIT Kanpur, he has worked in the Durgapur Steel Plant for extended period.