Strategic and Operational Management with Optimization at Tata Steel

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Tata Steel has been striving to optimize its operations amidst scarce resources and capacity imbalances. To provide decision support, we developed a mathematical model based on mixed-integer linear-programming (MILP) and hierarchical optimization between 1983 and 1986. It considers marketing constraints, capacities, yields, profitability, routes, energy, and oxygen balances. Its use just for optimal distribution of power has provided a benefit of US $73 million in the first year of implementation (1986–1987). Tata Steel has realized other benefits, such as optimal distribution of scarce oxygen and liquid iron, optimal power cogeneration levels, break-even prices and quantities of purchased scrap, and optimal conversion of semifinished steel into finished products by other companies functioning as conversion agents. In the early '80s, the model shifted Tata Steel's emphasis from maximizing tonnage to maximizing contribution to profits.

The Tata Iron and Steel Company Ltd., established in 1907 at Jamshedpur, is one of the largest companies in India. With capital investments of about $1,700 million, Tata Steel earns revenues of $1,100 million. The company employs 75,000 people and earns a profit of about $160 million on an annual production volume of 2.4 million tons.

The manufacturing facilities at Jamshed-

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INDUSTRIES—MINING/METALS
PROGRAMMING—INTEGER

pur consist of seven blast furnaces, four steel melt shops, both ingot and continous casting facilities, two primary mills, and seven finishing mills. The company also has captive oxygen plants, electrical power plants, and maintenance units. It does the primary rolling of ingots in the blooming mills and the final rolling at one of its finishing mills. The finishing mills include a sheet mill, a merchant mill, a bar forge shop, a narrow and a wide strip mill, a medium-and-light structural mill, a bar-and-rod mill, three tube-making plants, an agricultural-implements mill, a ring plant, and a bearing unit.

Tata Steel's product spectrum, one of the widest in the world, includes billets, bars, structurals, narrow and wide strips, black and galvanized sheets, electrical sheets, forged rounds, rolled and forged rings, axles, tubes, ball bearings, agricultural implements, and cement. Its tube division produces seamless, electric-resistance-welded and high-frequency-induction-welded tubes.

The Optimization Project

Tata Steel completed the first phase of its modernization in 1984. The company spent about $180 million. Management wanted to know the optimal allocation of its enhanced steel-making capacity so that it could maximize its contribution to profit and overhead. It assigned this task to a group working in the senior general manager's (Works) office, later designated "plant engineering and process analysis" (PEPA). Today the group, known as Operational Research, functions as the MS/OR wing of the company, providing decision support for optimizing the use of constrained resources.

Because the problem is dynamic, with capacities and resources varying from period to period, it was considered prudent to formulate a mathematical model of the production system, the works-planning model. The formulation, with some approximation, can be solved in the framework of a mixed-integer linear program (MILP). Data about various products and processes are expressed mainly in terms of capacities of processors (production facilities), the operating hours per ton of products in each facility, the yield of various products, and the routes of different products. In addition, we obtained oxygen rates (normal cubic meter per ton), scrap rates (kg/ton of crude steel), and thermal energy rates (Gcal/ton) at each facility from statistics on past performance. The model accepts maximum demand and minimum demand as marketing bounds.

The works planning model provides information on the optimal product mix. It can also determine the consequences of various options on the overall profitability of the steel division. After we developed the model, Tata Steel discontinued using the manual planning method in 1985 in favor of model-based planning.

In the financial year 1986–1987 (April 1986–March 1987), the company had an unforseen power crisis (Figure 1). A few months into the year (April to September), Tata Steel realized that although it had increased production, the contribution to profit had dropped substantially compared to the same period of the previous year. One of the chief reasons was that it operated the plant with the objective of maximizing production, believing that maximizing production would lead to maximizing

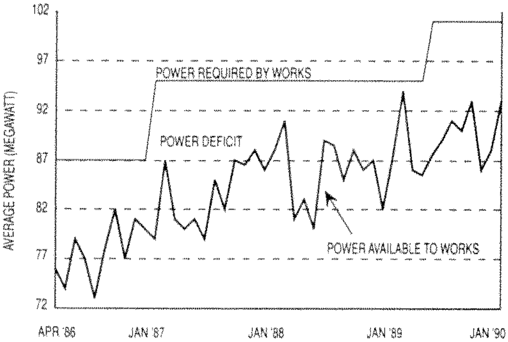

Figure 1: With modernization, Tata Steel's demand for power continually exceeds the availability of power.

profits. Therefore to cope with power crises, it was traditional to switch off first the mills at the finishing end—the strip mill, the merchant mill, the medium and light structural mill, and so forth. This helped keep the upstream facilities, the primary mills, running almost uninterrupted despite cuts in power. Since the semifinished output from the primary mills is saleable, the output tonnage of the company did not fall; in fact it went up a bit because there were no losses in secondary rolling. Thus the company rolled more semifinished products, which have a higher yield from the same materials and consume less power, thereby managing higher output despite power shortages. However, this output earned it very poor profits.

The PEPA group was given the task of maximizing the works contribution to profit by optimizing the use of scarce power. In the first step, we supplemented the works-planning model with electrical and thermal energy balance equations. The resulting model was named the works power model. We validated it by recreating the previous several months' operations on computer; tuning and fine-tuning parameters to minimize the deviations between simulated and actual values. Several operational characteristics were brought to light for the first time. Most important among them was our finding about fixed and variable power consumption and our estimation of the rates for each of the processors. We used the validated model to determine the optimal distribution of the available electrical energy. Based on the results of numerous runs of this optimizing model, we developed a set of decision rules for optimal allocation of available power. The model was partially implemented in November 1986 and fully implemented beginning in December 1987. The model is continually updated and used for decision support in situations in which resources are scarce.

Material Flow

Tata Steel is a fully integrated iron- and steel-making plant (Figure 2). It uses blast furnaces to convert iron ore, sinter, and other raw materials into molten iron, which is called hot metal. The hot metal goes to the steel melt shops, which use three processes to make steel: BOF (basic oxygen furnace), OHF (open hearth furnace), and EOF (energy optimizing furnace). From the BOF and the EOF, liquid steel goes to the continuous caster or it is cast into ingot moulds. Molten steel from the OHF is cast into ingots. Ingots are charged into the soaking pits, where they are heated and soaked so that their temperature profile is nearly uniform, and then they are rolled into heavier sections, known as blooms and slabs, in the blooming mills. The blooms are further rolled in the sheet bar and billet mills into sheet

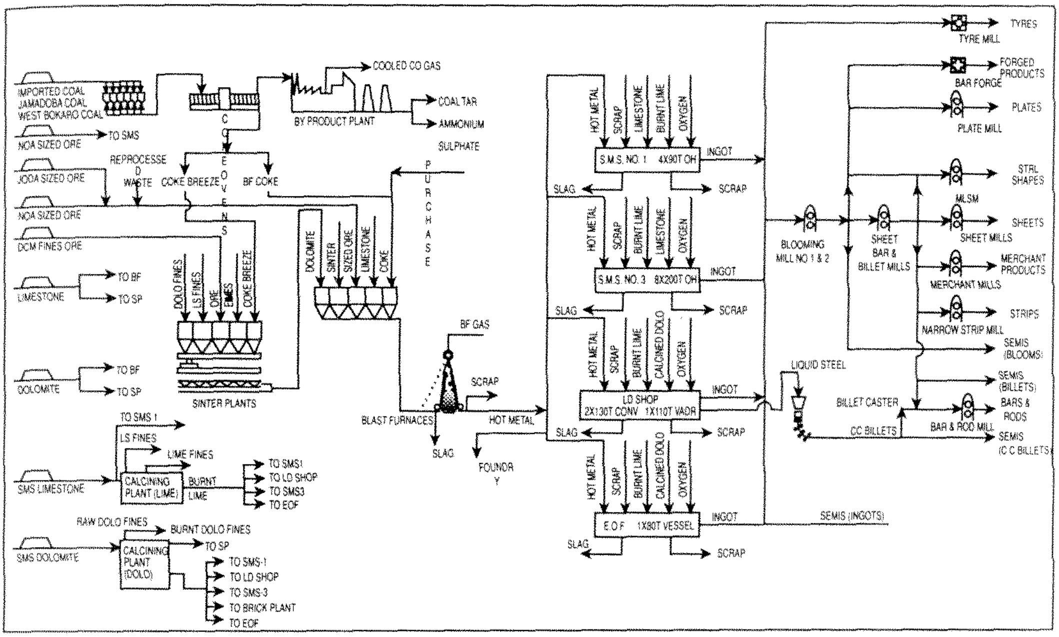

Figure 2: As materials flow from left to right in the diagram, they are converted into value-added products.

bars, strip bars, or billets. Sheet bars are then rolled in the sheet mills into ordinary, high silicon, deep-drawing quality and galvanized sheets.

The strip mill converts strip bars into high carbon or ordinary strips, which either go to market or to the tubes division. Billets from the sheet bar and billet mills are sent to the merchant mills where they are rolled into bars, angles, and octagons. The blooms are sent to the medium and light structural mill where they are further rolled into seamless gothic bars for seamless tubes or rolled as structural. Tata Steel employs external conversion agents to roll the balance of the semifinished products into finished products. It has installed a new slab caster to cast slabs directly from liquid steel from the BOF shops, also known as the L D shops.

Power Flow

The plant obtains its electrical energy from captive generating plants and from external sources. It obtains almost half of its needs from Tata's own thermal power plants. The company purchases the remainder of the power it requires from such external agencies as BSEB (Bihar State Electricity Board) and DVC (Damodar Valley Corporation). Moreover, the company is contractually obliged to allocate a portion of the power it purchases to the associated companies in Jamshedpur and also to the township. The problem of distributing power has four facets:

(1) Supplies from external sources are fluctuating and insufficient;

(2) Supplies vary during the day as they meet township and office loads;

(3) Some power supplies are essential to

keep vital units running and to meet the fixed load; and
(4) Tata Steel's need for power is increasing because of modernization.

Power Consumption

Two types of units consume power:
(1) Those having fixed and variable loads, and
(2) Those having only fixed loads.
During power shortages, the variable load of any processor is of primary importance. We use the term *processor* to mean any production unit, such as a steel-making unit, an iron-making unit, a primary mill, a finishing mill, or a tube-manufacturing plant. A blooming mill is a production facility, and an oxygen plant is a service facility, but both are termed processors. When a processor (say a particular mill) is running, the variable load is added to the system. Similarly when the mill is electrically switched off, that variable load leaves the power system. Therefore estimating the variable power requirement is the first step in building a model of the system. For processors having fixed and variable loads, we analyzed the correlations between monthly total KWH (kilowatt hours) consumed and monthly production tonnages using historical data. Because we found the correlation coefficients to be very significant, we used simple linear regression techniques to determine the fixed and variable components of the power load. Using total power consumption as the variable dependent on production tonnage, we plotted the best-fit equation for each mill. We used the Y-intercept to estimate the fixed load per unit of time; for example (KWH per month or just KW) and processed the slope to determine the variable component of power

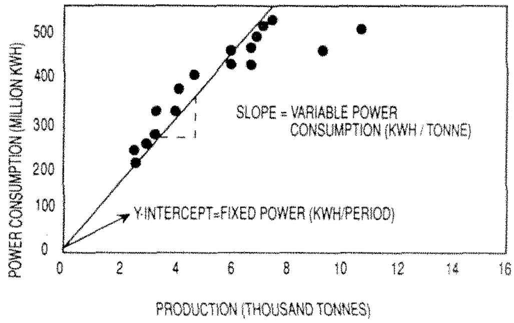

Figure 3: This scatter diagram plots total electrical energy consumed by a production unit as a function of its total output and shows a line of best fit.

use, expressed as KWH per ton (Figure 3).

The Problem of Allocating Power

The supply of electrical power from external sources sometimes fluctuates. The net power available to the steel works fluctuates even within an hour. Fluctuations are abrupt, although there are two cyclical variations—one has a 24-hour cycle with two peaks and the other has annual periodicity.

Tata Steel has four captive generating plants, some of which have been in operation for more than 40 years.

A minimum amount of power is always required to keep essential units, such as blast furnaces and pump houses, running. Failure to provide power for the water cooling systems of the blast furnaces would cause extensive damage to the blast furnaces and very high losses. Similarly, failure to supply power to the pump houses could have disastrous consequences. Therefore, any power allocation rule must consider a fixed amount as essential load.

Primary mills require a large amount of power when a bloom passes through the rolls but have a short start-up (setup) time, whereas finishing mills have low power requirements but have long start-up times.

Tata Steel must supply a portion of the power it buys to different associated companies and to the township. The town load varies according to the time of day, with the maximum demand occurring between 6:00 and 9:00 PM. The company is expected to continue supplying power to the town in the evening so that it doesn't cause a black-out.

The oxygen used for steel making comes from captive oxygen plants; two of these produce 250 tons per day (tpd) each, one 100 tpd, and one 500 tpd. The plants can vary their oxygen generation within a narrow range of these capacities. For example, a 250 tpd plant can produce between 200 and 250 tons per day. Within this range, power consumption varies linearly. By totally shutting down a plant, one can also save the fixed power. Running combinations of the plants would thus give different amounts of oxygen, sometimes varying in power consumption in a stepped manner. Oxygen is power intensive and it is a major determinant of steel production. Therefore, optimal oxygen production is important during a power crunch.

In addition to these complexities, the mathematical model must also account for the existing distribution network.

Mathematical Model

To consider simultaneously the numerous interdependencies and derive an optimal solution under varying conditions,

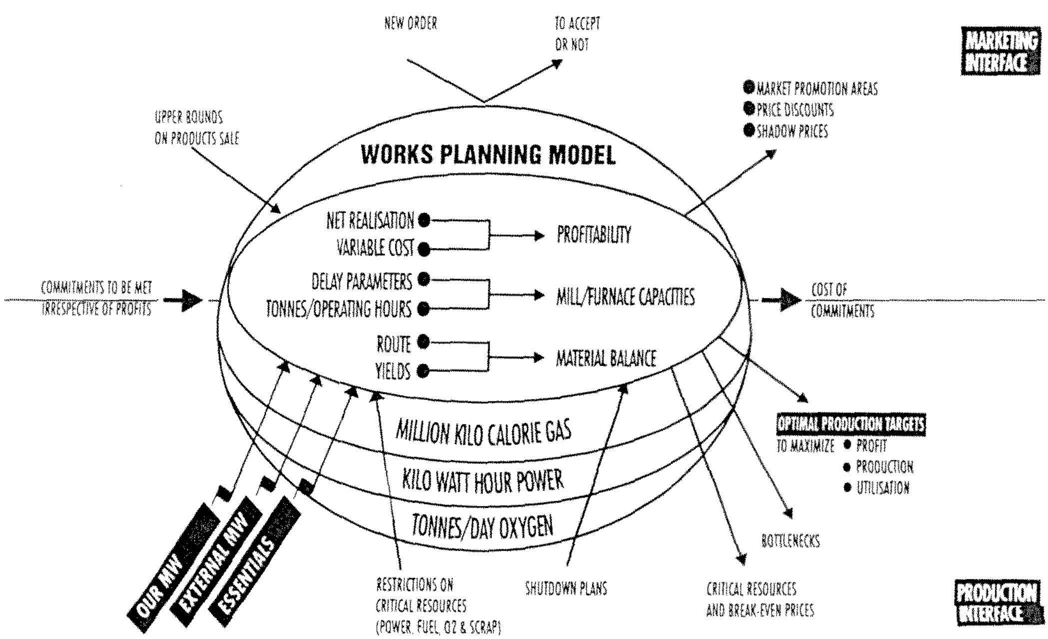

Figure 4: In this conceptual diagram of the works planning model, the upper half represents its interface with the marketing while the lower half depicts the production interface. The functions shown in the core are built into the model. Data on available electrical power, commitments, resource availability, demand, and shutdown plans are input into the model. Its output includes optimal production targets, data on critical resources and break-even prices, costs, and the like.

Tata Steel needed a mathematical model (Figure 4). The mathematical formulation developed (appendix) was greatly influenced by earlier work.

Baker, Clark, and Frund [1987] transformed a mainframe-based computer model for planning production and standard costing for Bethlehem Steel to a microcomputer-based system using Lotus 1-2-3. The model answers many what-if questions, such as how many shifts per week would the plate mill run and how would the final cost of the product be affected if the price of natural gas were to

Time p.m.	2	3	4	5	6	7	8	9	10
External restriction (MVA)	55	55	55	35	35	35	35	35	35
External MW to works	28	25	25	16	15	15	16	17	18
Our generation (MW)	86	88	88	90	90	88	87	86	88
Total MW available to works	114	113	113	106	105	103	103	103	106
PROCESSORS									
P3	off	off	off	off	off	off	off	off	off
P4	off	off	off	off	off	off	off	off	off
P11	off	off	off	off	off	off	off	off	off
P9	on	on	on	off	off	off	off	off	off
P10	on	on	on	off	off	off	off	off	off
P8	on	on	on	off	off	off	off	off	off
P5	on	on	on	on	on	off	off	off	on
P6	ws	ws	ws	ws	ws	ws	ws	ws	ws
P12	on	on	on	on	on	off	off	off	on
P1	on	on	on	on	on	on	on	on	on
P2	ms	ms	ms	ms	ms	ms	ms	ms	ms
P7	on	on	on	on	on	on	on	on	on

Signed by
B' Shift

off	Down for power
on	Mill running
ws	Weekly shutdown
ms	Major shutdown

Figure 5: The off/on chart shows the optimum operational status of various units according to the availability of power.

increase by 20 percent?

Ross and Kim [1980] devised a set of procedures and algorithms for dynamic and economic dispatch of generated power. The objective is to schedule the output so that the area load is met at the least cost. The method is based on successive-approximation dynamic programming.

Fukuda et al. [1987] have described the theoretical and practical solutions regarding forecasting and optimal control for energy distribution at a steel works. They used the ARMAX method to forecast energy and the gradient method to optimize energy distribution.

We solve the optimizing model (appendix) using a mixed-integer linear-programming algorithm (MILP). For a given set of conditions regarding the availability of power from external and in-house generation and depending on the essential loads, the model indicates what units to run to utilize the available power in the most profitable manner. It also gives the optimal product mix and the shadow contribution of various debottlenecking efforts.

For longer-range planning of production levels and resources, one can use a multiperiod version of the model. Interperiod linkages are provided by the inventories.

From Optimal Solution to Decision Rules

The optimal solution obtained showed great potential for increasing Tata Steel's profits. However, the basic input, that is, the power available to the steel works, changes continuously even within an hour. The changes in power availability have several components: some are abrupt, some are seasonal, and some, such as township and office requirements, have daily cycles. To implement the model to respond to such a changing scenario, we run the model and interpret the results very frequently. Each run would give a solution to a snapshot view of the changing scenario. To facilitate implementation under these varying conditions, we developed decision tables (Figure 5) to show the direction of optimality by running the model for various levels of power-input values and for various conditions of in-process inventories. To produce solutions that would be implemented easily, we determined "turning points," that is, points at which an on-condition gets changed to off and vice versa. The idea was to identify cutoff points for control variables, derived through multiple snapshot solutions. The shutdown priorities derived from such a chart, when combined with a daily schedule of the power required by the township

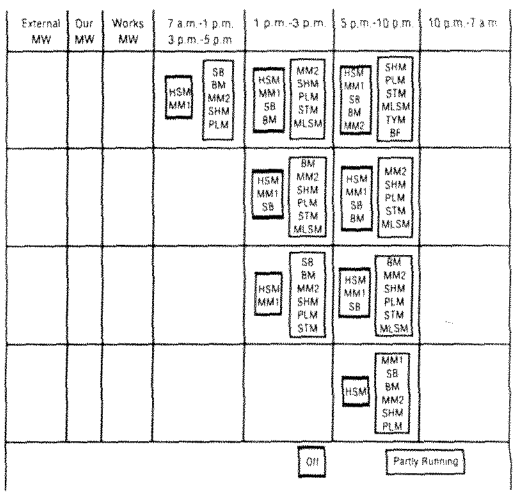

Figure 6: To implement the optimal distribution of scarce power, we derived decision rules for the sequence of shutoffs depending on the availability of power (rows) and the clock time. The township and office loads, which affect the power available to the works, vary according to the time of day.

and offices, result in an on-off decision chart, a reduced version of which is shown in Figure 6.

This shift from optimal solution to decision rules was a new approach that facilitated the implementation of a hard core OR solution for a continuously changing scenario. The optimal solutions had not been accepted readily by the operators controlling the switches. They found these solutions valid only for snapshot views of the situation, whereas they were expected to steer through a continuously changing scenario. Further, some operators took frequent instructions provided by the model as encroachments on their areas of decision making. However, the on-off decision charts were too simple to resist, and they relieved PEPA of the task of minute-to-minute monitoring.

Implementation

Based on the high benefit potential shown by the model for the months of April through September 1986, we made a series of presentations in October 1986. The radical strategic changes suggested met with so much resistance and doubt that the president asked the accounting department to vet the results. We spent days and days around the clock explaining every ton shift. The model helped to answer all the questions, and it generated slow but steady conviction. Still no go-ahead signal was coming. Lo and behold, in the last week of October, the power dipped further, and the president, without waiting for the vetting, asked us to try out the model. PEPA kept daily track of the estimates of contributions under both new and old strategies. After a few days trial, the gains were visible, and the informal implementation continued through November. The results during November spoke louder than the whole MS/OR team. Compared to the preceeding month, less power was available and production was lower, but the contribution to earnings was up (Figure 7)! The power of optimization was certainly visible. On November 30, 1986, in a special meeting convened in the boardroom, the president, Dr. Jamshed J. Irani, ordered a round-the-clock implementation of the model. A power cell, comprising two officers per eight-hour shift, was formed. This cell monitored hourly generation and the external MW available and also saw that the mills were switched on and off strictly according to the decision rules.

Before the model was developed, it was traditional to shut down finishing mills

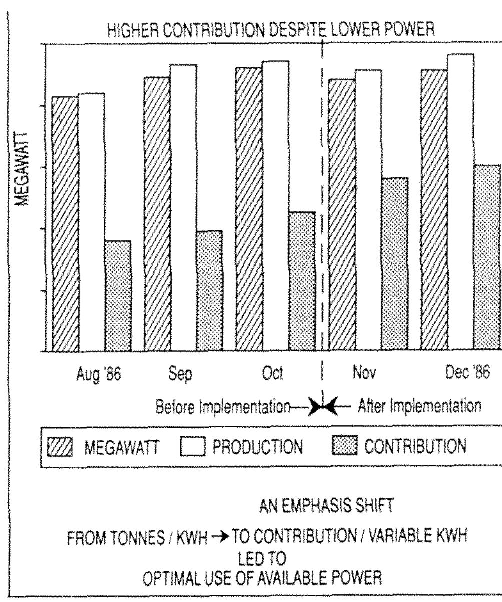

Figure 7: With implementation of the decision rules, despite lower power availability and lower production, the contribution to earnings increased.

first. But the model showed that only a few of the finishing mills should be shut down before the primary mills, and most of the finishing mills should be shut down after the primary mills. It also sold Tata Steel the idea that in a power crisis, contribution per KWH is a more important factor than contribution per ton.

At low levels of power availability, the marginal contribution of power is very high but as the availability of power increases the marginal contribution of power decreases. This means that situations of power surplus and power deficit are not the same. When power is short, the finishing mills are not fully loaded, and an additional MW of power will improve their contribution substantially. In such a case (Figure 8), it was possible to utilize one extra MW of power by running one finishing mill. But when there is surplus power, all mills are fully loaded and one additional MW of power will not improve profitability because no processor is left to be utilized to make more steel and generate more revenue.

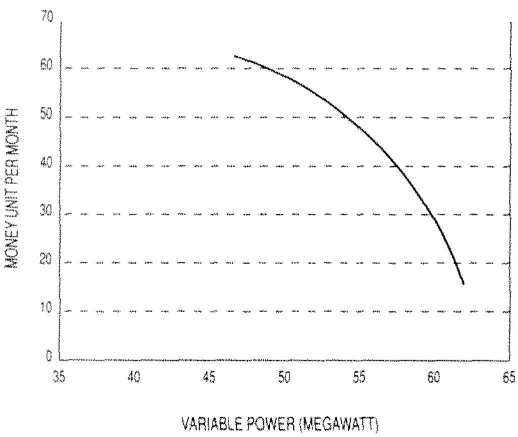

Figure 8: At low levels of availability, the marginal contribution of power is very high; as power becomes abundant, its incremental contribution drops sharply.

The model justified installation of diesel generating units. It showed that at certain levels it was more profitable to purchase oil, generate more expensive power, and produce steel than it was to keep the finishing mills idle.

Based on the findings of the model, management decided to stop purchasing external scrap when power was scarce. Based on the model management also decided to stop producing some products. Initially, the model was confined to the steel division. In 1990, management decided to extend it to the tubes division and the Tinplate Company of India Limited (TCIL). Further, in 1992, top management decided to allocate preferential power to Indian Steel Wire Products Limited (ISWP), a wire rope company that also acts as a conversion agent for Tata Steel.

Tangible and Intangible Benefits

The model was informally implemented on a trial basis in November 1986. Beginning in December 1986, it was implemented around the clock with a power cell formed to insure its use. We estimated benefits by comparing the contribution per mw-hr before and after implementation. For the first year of implementation, 1986 to 1987, the contribution to profits per mw-hr increased from \$398.00 to \$648.00 (Table 1).

The benefits to two other organizations (the Tinplate Company of India Limited and Indian Steel Wire Products Limited) are not included. Also, we have not included the benefits from using the power model after March 1987 and from using optimal product-mix decisions during power surplus situations for the last six

	Average MW	Electrical energy consumed in works MW Hour	Works contribution $ Million	Works contribution $/MW Hour	Contribtution without the model $ Million	Gain due to model during November 1986 to March 1987 $ Million
April 1986	76	54,720	19.29	353		
May 1986	74	55,060	23.18	421		
June 1986	79	56,880	19.65	345		
July 1986	79	58,780	24.36	414		
August 1986	73	54,310	20.30	374		
September 1986	78	56,160	23.43	417		
October 1986	82	61,010	28.03	459		
(Apr 1986–Oct 1986)						
Total		396,920	158.24		158.24	
Average				398		
November 1986	77	55,440	35.92	648		
December 1986	81	60,260	40.15	666		
January 1987	80	59,520	40.05	673		
February 1987	83	55,780	36.85	660		
March 1987	85	63,240	37.78	597		
(Nov 1986–Mar 1987)						
Total		294,240	190.75		117.30	73
Average				648		

Table 1: The implementation of the power model increased contribution per MW hour from $398 to $648. The available electrical energy from November 1986 to March 1987 was 294,240 MWH and the gain due to implementation of the model was 294,240 × (648 − 398) = $73 million.

years. The intangible but most significant benefit of the model was the credibility and acceptance of the results that came from implementing the management science model and the interaction of decision makers with the model.

In addition, substantial benefits accrued from timely decisions based on other uses of the model. Some of those worth mentioning follow:

—Optimal distribution of scarce oxygen during oxygen plant failures;

—Optimal hot metal distribution during blast furnace failures;

—The installation of diesel generating units based on their marginal contribution of power;

—The purchase of scrap during shortages of hot metal in accordance with break-even prices and quantities revealed by the model; and

—Optimal levels of conversion of semifinished products into finished steel by other companies.

The model brought about a complete turnaround in management strategy, a shift in emphasis from maximizing tonnage to maximizing contribution to profit.

Acknowledgment

We are thankful to Dr. Jamshed J. Irani, CEO and Managing Director; K. C. Mehra; Dr. T. Mukherjee; R. P. Tyagi; and F. A. Vandrevala for continuous guidance and support in carrying out the optimization

exercises for the benefit of Tata Steel.

APPENDIX

The mathematical formulation is designed to optimize the specified objective functions in a constrained situation.

Decision Variables (Real)

IN_{jkt} = the inventory of the k-th item at the j-th processor at the end of the t-th period,

PRCHLQFL = liquid fuel to be purchased to meet a thermal deficit,

X_{jk} = production of the k-th item at the j-th processor,

X_{jk}^{r} = the rollable portion of X_{jk}, and

X_{jk}^{s} = the saleable portion of X_{jk}.

Decision Variables (Integer)

NEOF = number of energy optimizing furnaces (EOF) in operation,

NTNNG = number of tonnage oxygen plants in operation, and

NTNNX = number of tonnox oxygen plants in operation.

Decision Variables (Integer: 0/1 Type)

ISWBSE = Indian Steel Wire Products Ltd. (ISWP) on Bihar State Electricity Board (BSEB) grid,

ISWTIS = Indian Steel Wire Products Ltd. on Tata Steel/Damodar Valley Corporation (DVC) grid,

TPBSE = Tinplate Company of India on BSEB grid, and

TPTIS = Tinplate Company of India on Tata Steel/DVC grid.

Variables (Real)

DVCTISMW = DVC power drawn by the Tata Steel grid,

FXDO2 = sum of all fixed oxygen requirements,

FXDO2MW = fixed power required by oxygen plants,

IDLO2EOF = idling oxygen consumption of EOFs,

ISWBSEMW = power supplied to ISWP from BSEB grid,

ISWTISMW = DVC power supplied to ISWP from Tata Steel grid,

MKC_{jk} = million kilocalories consumed per ton of kth product at the j-th processor,

MKCEXT = million kilocalories of external fuel consumed,

MKCFXD = fixed million kilocalories required for running a steel plant,

MKCLOST = million kilocalories lost in the calorie balance,

MKCS3 = total million kilocalories spent in open hearth furnaces of SMS3 during the period,

$O2GEN_{p}$ = oxygen generation of the p-th oxygen plant,

O2S3 = total oxygen consumed in open hearth furnaces of SMS3 for the period,

S3PRD = total output from open hearth furnaces of SMS3 during the period,

TDTISMW = DVC power supplied to tube division,

TPBSEMW = BSEB power drawn by TCIL, and

TPTISMW = DVC power supplied to TCIL from Tata Steel grid.

Parameters

$AVLBLT_{j}$ = fraction availability of processor j,

BSEBMW = expected supply of power from BSEB,

CVLQFL = calorific value of purchased liquid fuel,

DLO2EOF = fixed oxygen consumption rate of EOF per period per operating EOF regardless of whether it is running or idling,

$DMAX_{jk}$ = maximum units of k-th product from j-th processor that the market can absorb,

$DMIN_{jk}$ = minimum committed units of k-th product from j-th processor that must be supplied, regardless of gain or loss,

DVCMW = expected supply of power from DVC,

EXTMW = expected power available from the external sources,

EXTPCON = expected power consumption of the external sources,

FXDCON = fixed power requirement of the

works (sum of all essential loads and the fixed part of nonessential loads),
$FXDO2TNG$ = fixed power consumed by tonnage plants,
$FXDO2TNX$ = fixed power consumed by tonnox plants,
GPO = general purpose oxygen requirement,
H_j = total calendar hours for the j-th processor,
HRS = calendar hours during the planning horizon,
$KWHT_{jk}$ = KWH per ton of k-th product at the j-th processor,
$MKCGEN_{jk}$ = net million calories generated per ton of production of the k-th product at the j-th processor, (Applicable for calorie generating units, such as the blast furnaces, which generate blast furnace gas; coke ovens which generate coke oven gas, and LD (Linz Donawitz) shops, which generate LD gas)
NR_{jk} = net realization (dollars/ton) of the k-th grade of saleable steel from the j-th processor,
O_{jk} = oxygen consumption at the j-th processor for the k-th product,
$OHPT_{jk}$ = operating hours per ton of k-th product in the j-th processor,
RMW = expected power generation from the captive sources.
SD_j = planned shutdown hours for j-th processors during the planning horizon,
VC_{jk} = variable cost of the k-th product of the j-th processor, and
YLD_{jk} = yield of the k-th product in the j-th processor.

Objective Functions

The model works with each of the following optimizers:

Maximize contribution to profit

$$\text{maximize } Z = \sum_j \sum_k (NR_{jk} * X^s_{jk}) - \sum_j \sum_k (VC_{jk} * X_{jk}), \quad (1)$$

minimize cost

$$\text{minimize } Z = \sum_j \sum_k (VC_{jk} * X_{jk}). \quad (2)$$

Maximize production

$$\text{maximize } Z = \sum_j \sum_k X^s_{jk}. \quad (3)$$

Constraints (Real)

Capacity balance

$$\sum_k (X_{jk} * OHPT_{jk}) < (H_j - SD_j) * (AVLBLT_j) \cdots \quad \forall j. \quad (4)$$

Material balance

$$X_{jk} = \sum_{k'} \sum_{j'} (Xj'k' / YLDj'k') \cdots \quad \forall j, k, \quad (5)$$

where j's are immediate downstream processors to processor j and k's are next descendent product.

Electrical energy balance

Kilowatt hours consumed < Kilowatt hours (generated and purchased)

$$\sum \sum (X_{jk} * KWH_{jk}) < HRS * 1000 * (RMW + EXTMW - EXTPCON - FXDCON), \quad (6)$$

Hours = 672/696/720/744 for 28/29/30/31 day months respectively.

Oxygen balance

$$\sum_j \sum_k (O_{jk} * X_{jk}) + FXDO2 < \sum_p O2GEN_p \quad (7)$$

$$FXDO2 = IDLO2EOF + GPO. \quad (7a)$$

Thermal balance

Million kilocalories consumed ((fixed + variable) + lost) < Million kilocalories (generated and purchased)

$$\sum_j \sum_k (X_{jk} * MKC_{jk}) + MKCFXD + MKCLOST < (X_{jk} * MKCGEN_{jk}) + MKCEXT\ MKCEXT = \text{PRCHLQFL} \cdot \text{CVLQFL}. \quad (8)$$

Minimum demand (commitments)

$$X^s_{jk} > DMIN_{jk} \cdots \quad \forall j, k. \quad (9)$$

Maximum demand (marketing restrictions)

$$X^s_{jk} < DMAX_{jk} \cdots \quad \forall j, k, \quad (10)$$

$$X_{jk} = X^s_{jk} + X^r_{jk} \cdots \quad \forall j, k. \tag{11}$$

Constraints (Integer)
Oxygen consumption during idling of EOFs

$$IDLO2EOF = DLO2EOF*NEOF.$$

Fixed-power consumption of oxygen units

$$FXDO2MW = FXDO2TNG*NTNNG + FXDO2TNX*NTNX.$$

Gridability constraints
These constraints arise because the power from the two suppliers DVC and BSEB cannot be put on the same grid owing to frequency mismatches.

DVC Flow

$$DVCMW = DVCTISMW + TPTISMW + ISWTISMW + TDTISMW,$$

BSEB Flow

$$BSEBMW = TPBSEBMW + ISWBSEMW.$$

Associate companies on one of the grids (on-off constraints)

$$TPBSE + TPTIS = 1,$$

$$ISWBSE + ISWTIS = 1.$$

Upper limits on power supplies to subsidiaries

$$TPTISMW < 10*TPTIS,$$

$$TPBSEMW < 10*TPBSE.$$

The model runs into about a thousand variables and a similar number of constraints with density of two to three percent. It is a mixed-integer linear-programming model and can be solved using branch-and-bound and revised simplex algorithms. In the initial stages of development, solutions were obtained through a mainframe computer, B6800 of Burroughs make. The software used was TEMPO (Techniques of Efficient Mathematical Programming for Optimization). The CPU time for each run used to be on the order of four to five minutes. When the B6800 system was retired, the model was transported to a VAX 3400 system (Digital Equipment Corporation), taking CPU time of one or two minutes.

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Jamshed J. Irani, Managing Director and CEO, The Tata Iron and Steel Company, Limited, Jamshedpur-831 001, India, writes, "The cumulative benefit realised from this model is approximately US $73 million. This model has become an integrated part of Tata Steel's decision-making process and has entirely changed the planning process in the Company. The OR/MS model has significantly contributed to maximising the Company's profits since 1986."