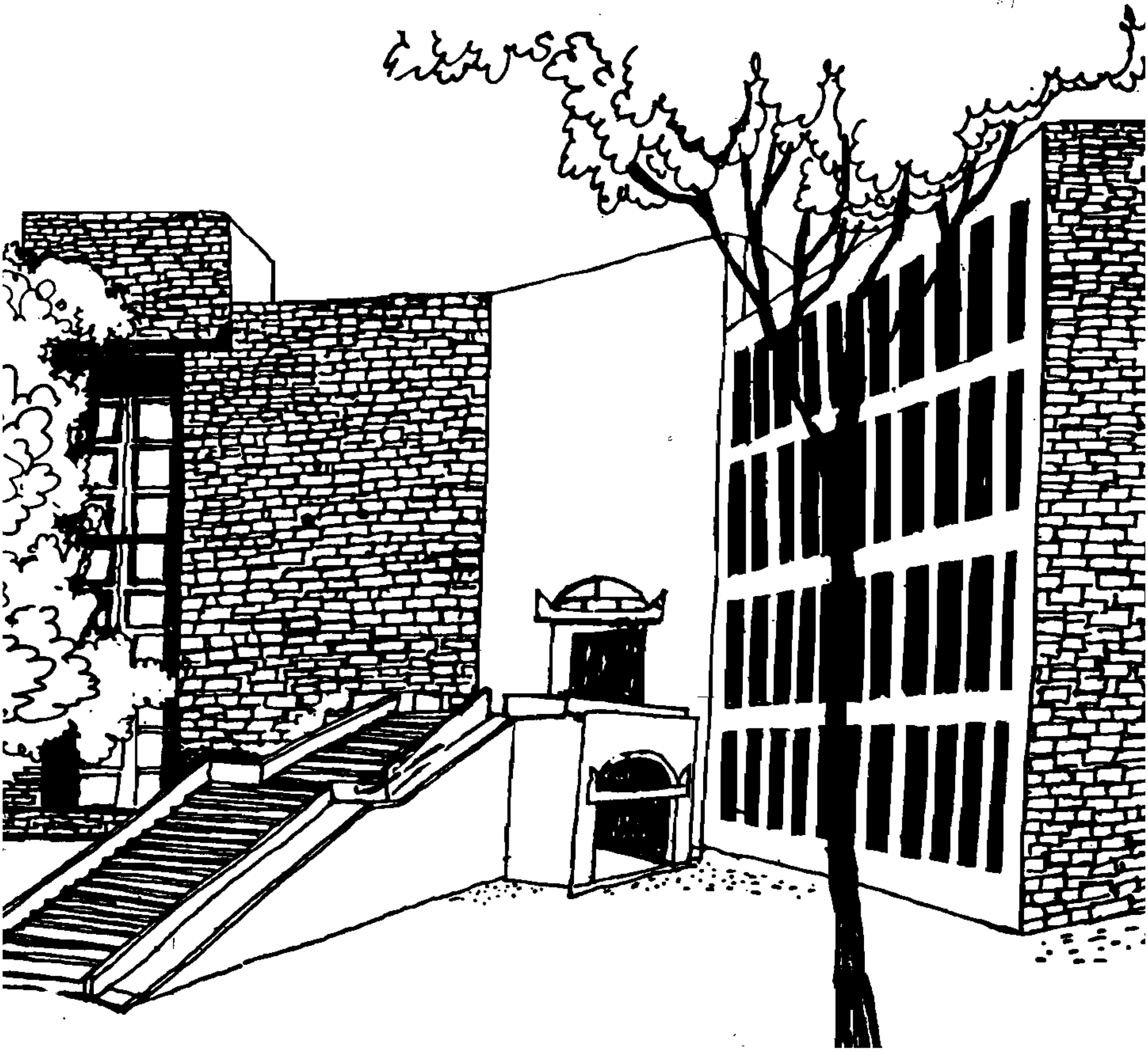
विद्याविनियोगाद्विकासः

IIM

AHMEDABAD

Working Paper



A SYSTEM DYNAMICS SIMULATION MODEL OF A BLAST FURNACE

By

Goutam Dutta
Medha Ashtekar

W.P.No.99-09-05
September 1999

INDIAN INSTITUTE OF MANAGEMENT
AHMEDABAD - 380 015
INDIA

A System Dynamics Simulation Model of a Blast Furnace

Goutam Dutta and Medha Ashtekar

Indian Institute of Management
Vastrapur, Ahmedabad-380015
India

Abstract

In this paper, we present a simulation model of a blast furnace. In a blast furnace the quality and productivity of the output (hot metal) depends on a large number of input variables and operating variables. The complex interactions of technological and financial variables have been simulated with the system dynamics methodology.

The model has been tested with the real data of one steel company in Southeast Asia.

1.Introduction

This project is an attempt to model a blast furnace of an integrated steel plant for investment decision. The focus of our research is on the complexity of the blast furnace of an integrated steel plant where the quality, productivity, and profitability of the output (hot metal) depend on many interacting variables. Hence, it is difficult for an analyst to predict the dynamics of changes in all the interacting variables in a blast furnace.

As the liquid steel produced from scrap in an electric arc furnace is cheaper than the hot metal produced in a blast furnace, many steel companies in industrialized countries are moving away from the blast furnace technology. Interestingly, the steel industry is also moving from developed countries to developing countries. A large number of steel companies from developing countries are still using blast furnace technology and would continue using it in the foreseeable future. The complexities of the technology and cost interdependencies make it difficult for a manager to predict the technical and financial outcomes, which affect various investment decisions.

Because of the complexities, when an investment decision is made with respect to a blast furnace, a manager relies on his/her intuition. This intuitive solution may not be the best course of action for a company that is looking for the optimal returns on investment. We chose system dynamics principles (Forrester, 1964) to simulate the blast furnace for project evaluation as useful aid to these managerial decisions. System dynamics incorporates cause and effect relationships, non-linearity and close loop feedback control.

The model developed in this paper is generic and can be used by other blast furnaces in any part of the world. The model can be used to discuss the following types of questions for investment decisions:

1. If a coal injection facility is installed with investment of X million dollars, will the productivity of blast furnace improve? If this improvement results in a reduction of the variable cost of production of hot metal, is the investment justified?

2. If imported coal is used as a raw material in the blast furnace, less coke is required per ton of hot metal. This is because of the fact imported coal contains less percentage of ash than that of domestic coal. However, the imported coal is more expensive than the domestic coal. Should this company be substituting domestic coal by imported coal?

3. Should more percentage of sinter as input raw material reduce the cost per ton of hot metal?

A study (Sinha and Dutta, 1985) was the first reported attempt of modeling a blast furnace in an integrated steel plant. This work was implemented in B6800 mainframe computer and used an ALGOL based DYNAMO computer. This work could not be carried out because of the restriction of the compiler of computer in 1985. With the availability of powerful computing facility, the second author of the above study decided to restart this work as an academic research.

In section 2, we give an overview of modeling of a blast furnace and system dynamics modeling of a steel plant. In section 3, we describe the technology of the blast furnace. Section 4 describes how we simulated the blast furnace with system dynamics methodology. Computer implementation and validation of the model is described in section 5.

2.Literature Survey

The first reported work (Fabian, 1958) of modeling an integrated steel plant is a linear programming model that minimizes the cost of production. It is an integration of four sub-models: an iron making sub-model, a steel making sub-model, a primary mill sub model and finishing mill sub-model. The iron making sub-model is an application of linear programming in the blast furnace. Another publication describes (Fabian, 1967) complete discussion of application of a linear programming in a blast furnace A later publication (Fukuo et. al, 1983) describes a selection system for finding the optimal operating condition of a blast furnace. Application of computers in blast furnace control is described in a series of reports (Oaknock et. al, 1983; Perez and Hanikar, 1983; Savas, 1961; and Sweeney et. al). These studies are based on linear programming, discrete event simulations or process control models.

Narchal (1988) has dealt with the problem of building a system dynamics simulation model for helping corporate planning in an integrated steel plant. The model is designed to ensure that material flow takes place through twelve production units arranged in six stages of production. Functioning of the model requires a time variant input demand of seventeen categories of finished steel products and three categories of raw materials. The management used the model for simulating the impact of their strategic policies on corporate objectives. The model also helped management in designing a long-term investment policy related to expansion and modernization and project smooth flow of production.

Dangerfield (1993) has presented a system dynamics model which shows that, for a typical integrated steel plant, the market response to lack of steel availability can more than offset any economies of scale in production costs. In addition, larger units with higher fixed costs are financially less able to withstand cyclical downturns in demand. As a result, plants having smaller blast furnaces are more profitable than those having larger furnaces. His work is related to a steel plant, but does not discuss any complexities of a process model of a blast furnace.

The blast furnace is always a matter of great challenge for OR analysts or modelers. Any process improvement and technology enhancement needs several million dollars of investment and there is no standard way to find out if the return is worthy of that investment. Sinha and Dutta (1985) choose system dynamics techniques to find out the returns on the investment of steel company made in the modernization in early 80s. This is the first use of system dynamics techniques in a blast furnace, where hot metal production is based on material balance equations. In the current paper, we have considered hot metal production as a non-linear function of several technological variables like productivity of blast furnace, working volume, and available hours in a blast furnace. Current work is also validated with the latest set of data.

3.Technology of a Blast Furnace

A blast furnace converts the (input) raw materials into (output) liquid iron, which is an input to steel making. Liquid iron is also known as hot metal. Blast furnace operates at a very high temperature (1500 degrees centigrade). The inputs are iron-bearing materials (iron ore, sinter, pellet, and ferro-manganese), coke which also acts as a reducing agent, and fluxes (like limestone and dolomite). Fluxes are used to remove impurities from iron ore. A more technical definition of the blast furnace would be called a gas-solid, counter-current, shaft type heat exchanger (as the materials inside the blast furnace are in a gaseous or solid state). Lankford et al, (1985) discuss the principles of blast furnace technology in more detail.

A schematic diagram of the blast furnace is shown in Figure 1. The different parts of a blast furnace are hearth, stack, bosh, tuyeres, bustle pipe, iron notch (metal notch), cinder (slag) notch, and mantle. Air (heated to a temperature of about 1200 degrees centigrade) is blown through the tuyeres for combustion. The liquid hot metal is tapped from the iron notch and the slag is collected from the cinder notch. The outputs of a blast furnace are hot metal, slag, and blast furnace gas (BF gas). BF gas is collected from the top and is cleaned in the gas cleaning plant. This gas is used as fuel to pre-heat the incoming air (used as hot blast).

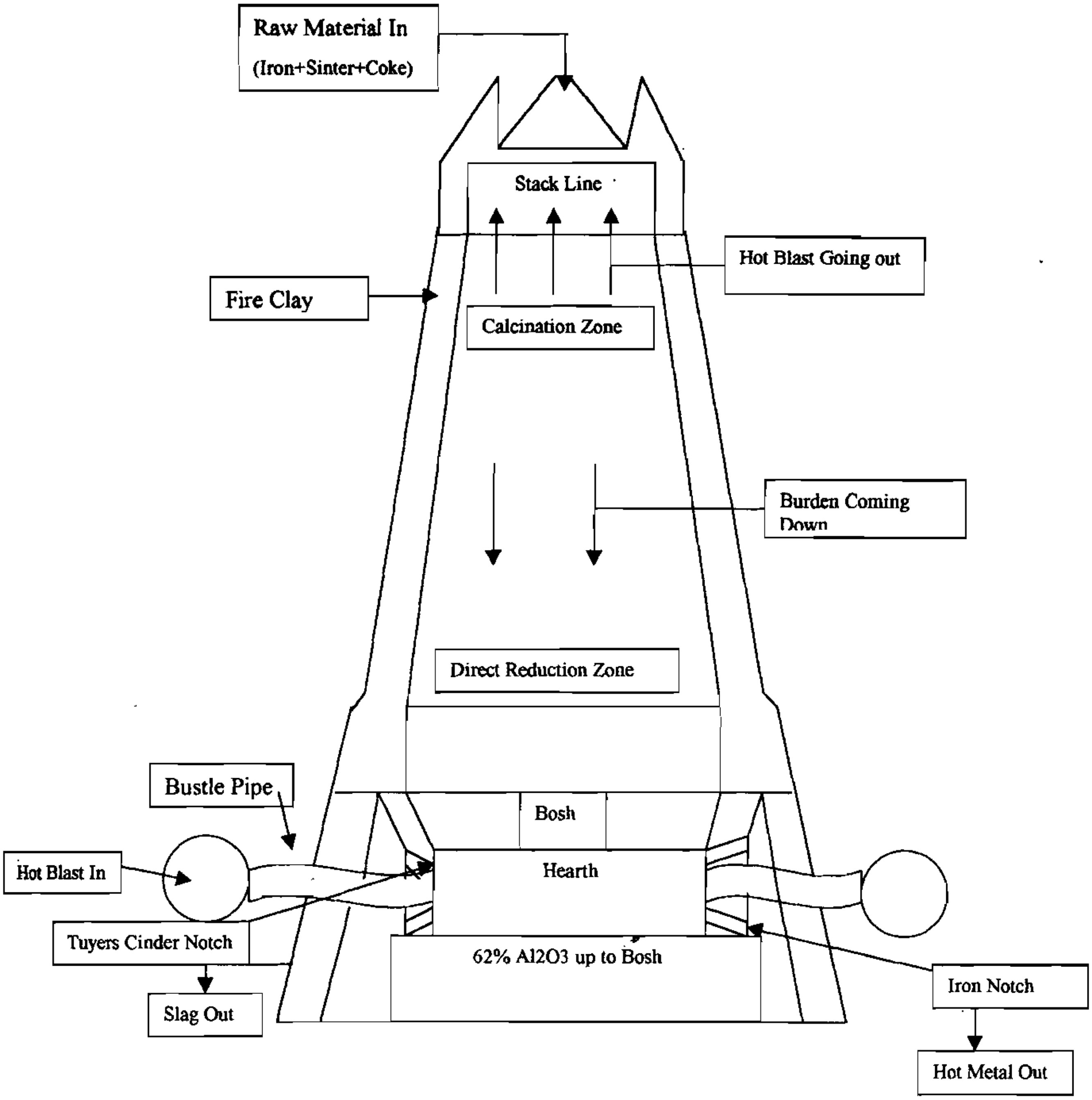


FIGURE 1 BLAST FURNACE

The impurities in the main inputs (ore and coke) call for fluxes like limestone and dolomite. Fluxes reduce the blast furnace volume available for iron ore processing and take away a portion of sensible heat, necessitating more of coke. Besides these input variables, other important factors are furnace downtime, raw materials availability particularly sintered ore, chemical analysis of coke and ore, and the demand of hot metal from steel making units.

We define some of the technological variables that are used in the mathematical model of the blast furnace.

The productivity of a blast furnace, defined as the amount of hot metal produced per unit volume of the blast furnace per unit time (tons/m^3/day), depends, to a large extent, on the rate and temperature of the air blast. Volume of the blast furnace is the volume at NTP (Normal Temperature and Pressure).

The coke rate, i.e. the amount of coke used as input raw material per ton of hot metal produced, is another important performance indicator as well as a cost influencer.

Sinter rate is the amount of sinter that is used as input raw material per ton of hot metal produced.

Ore rate is the amount of iron ore that is used as input raw material per ton of hot metal produced.

Hot metal generation rate depends mainly on the intensity of reducing atmosphere and the thermal profile inside the blast furnace caused by incomplete combustion of carbon. The rate of this combustion depends on the temperature and amount of hot air used per unit time.

The maximum possible wind rate depends on the top pressure and the permeability of burden that is mainly influenced by the burden composition, particularly the coke content, the size distribution, and the strength of coke.

4. System Dynamics Model

In this section we describe the basic principles of system dynamics (Forrester, 1964). System Dynamics is based on the principle of cause and effect relationships and feedback control. All cause and effect relationships and feedback control loops are described in a diagram called the *Influence Diagram*.

There are four types of variables in the system dynamics: levels, rates, auxiliary, multipliers. Rates are the dynamic variables, which change over time. Level variable is a storage variable. Level changes due to changes in the Rate variable and through rate variables only. Auxiliary variables do not have direct impact on Levels. Auxiliary variables have indirect impact on level through rate variable. There are multipliers or table function, which are predetermined variables drawn from actual values of the variables. In addition to above four types of variable there are constants.

The Blast Furnace model developed by us, has four sub-systems as follows: production subsystem, workforce subsystem, accounting and financial sub-system and information sub-system.

4.1 Production Subsystem

Production of hot metal in a blast furnace is computed from the productivity of the blast furnace, available hours per blast furnace, and working volume of the blast furnace. Productivity of the blast furnace is the amount of hot metal produced per blast furnace per day per working volume of the blast furnace. The productivity figures are entered as a table function. The steel plant we have chosen, has a number of blast furnaces and the total hot metal production is the sum of production of the furnaces. Calendar hours and downtime per blast furnace determine available hours per blast furnace. Calendar hours is a function of number of shifts per blast furnace, hours per shift and number of days per month per blast furnace. Downtime consists of planned delay (preventive shutdown), unplanned delay (breakdown maintenance), and capital repair and mid-term repair. Capital repair hours, mid-term repair hours, and breakdown hours are defined in the form of table functions of actual values of the parameters. Number of days per month is a table function of month. Base year of the model is 1995 and the financial year of the company (and the simulation model) starts from April.

Hot metal demand is a level variable with two rate variables: input demand rate and output demand rate. Hot metal demand is also related to hot metal inventory, which is another level variable. Hot metal demand and production of hot metal determine hot metal flow. Important inputs of raw materials are sinter, ore, and coke. Sinter charged in the blast furnace is the sinter produced in the sintering plant (as a table function) multiplied by the transfer loss of sinter (a parameter in the simulation model). The modeling of coke and ore are similar. Ore inventory is a level variable and so is ore consumption. Coke consumption is computed in this subsystem, which is an input to the financial subsystem for computation of gross factor cost of the inputs. Ore and coke inventories are also computed in this sub-system.

4.2 Workforce Subsystem

The workforce in the blast furnace consists of three components: operating crews, maintenance crew and, contract labourers. The operating and maintenance crew are regular employees of the company and contract labourers can be hired as and when required (mostly in maintenance). Life of a blast furnace is about five years after which it undergoes a major repair (known as relining). The period of a major reline varies from 58 to 75 days. In a five-year life span, a blast furnace can undergo one or two minor repairs of 15-30 days. Since the blast furnace is the heart of a steel plant, any delay (in the form of breakdown) can affect production. Therefore, the total amount of steel produced in an integrated steel plant is dependent on the amount of hot metal produced in the blast furnace.

4.3 Accounting and Financial Sub-system

In the financial model of the blast furnace, we have considered the price and cost structure of the blast furnace. The cost structure of the blast furnace is shown in Figure 2. We have also considered the inflation rate of the raw materials of the blast furnace. The material expense is the sum of the raw materials cost. The major components of material expenses are iron ore, coke, sinter, and fluxes. Net material expenses are gross material expenses minus the credit scrap and credit from blast furnace gas (generated as by-product). We add the cost above to the net material cost. The labour cost, the operating cost and GAGW (general administrative and general works cost) are parts of the cost above. We have modelled three different components of labour cost: regular operating crew, maintenance crew, and contract labour. In each component of the cost, we have considered different wage rates for different types of labour and their inflation rate. The number of maintenance personnel is dependent on the downtime for maintenance.

4.4 Management of Information Sub-systems

This subsystem computes various actual and possible rates like required hot metal production, maximum hot metal production, possible hot metal production, actual production losses owing to breakdown, mid-term repair and capital repair, maximum capacity in hours, available capacity in hours, utilised capacity, surplus man-hours, and shortage man-hours. The comparison of actual and possible rates can act as a policy making tool.

COST STRUCTURE OF A STEEL COMPANY

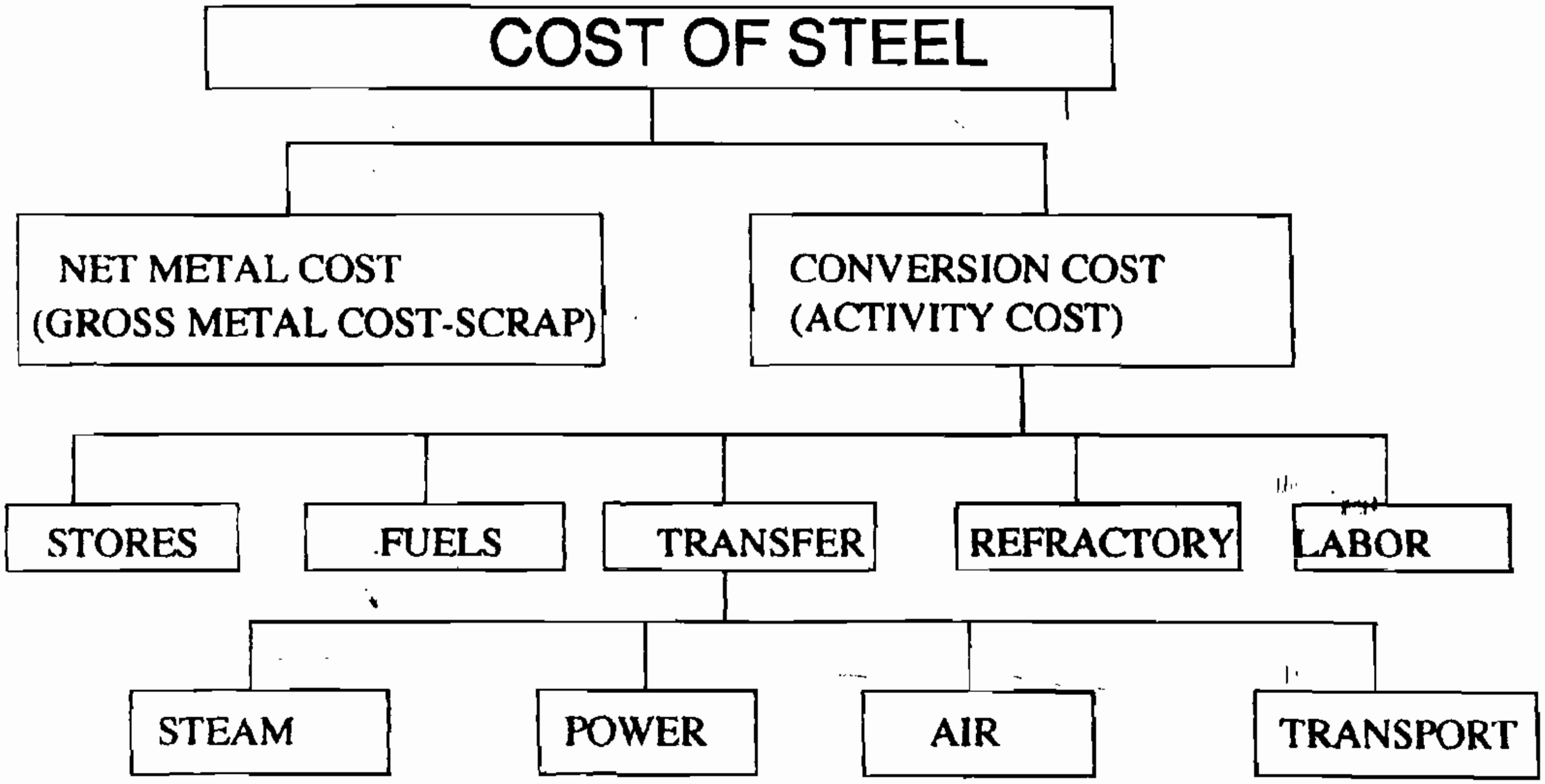


FIGURE 2

We now discuss some of the system dynamics loops [Figure 3] that we use in the model. These loops are based on the experiences of the blast furnace operators, maintenance crew, metallurgists and accountants.

1. When hot metal production increases, the number of hours required for capital repair increases, downtime increases and available hour decreases. With the decrease in available hours, possible production decreases, which in turn results in a decrease in hot metal production.

2. Increase in hot-metal production increases maintenance work, which increases delay. An increase in delay increases the downtime, which in turn decreases available hours. With the decrease in available hours, possible production decreases, which results in a decrease in hot metal production.

3. Coke rate depends on coke ash, fraction sinter in burden, slag rate, hot blast temperature, slag, rate and possible wind rate.

4. Flux rate depends on coke rate, coke ash, slag basicity, ore iron analysis and sinter iron analysis.

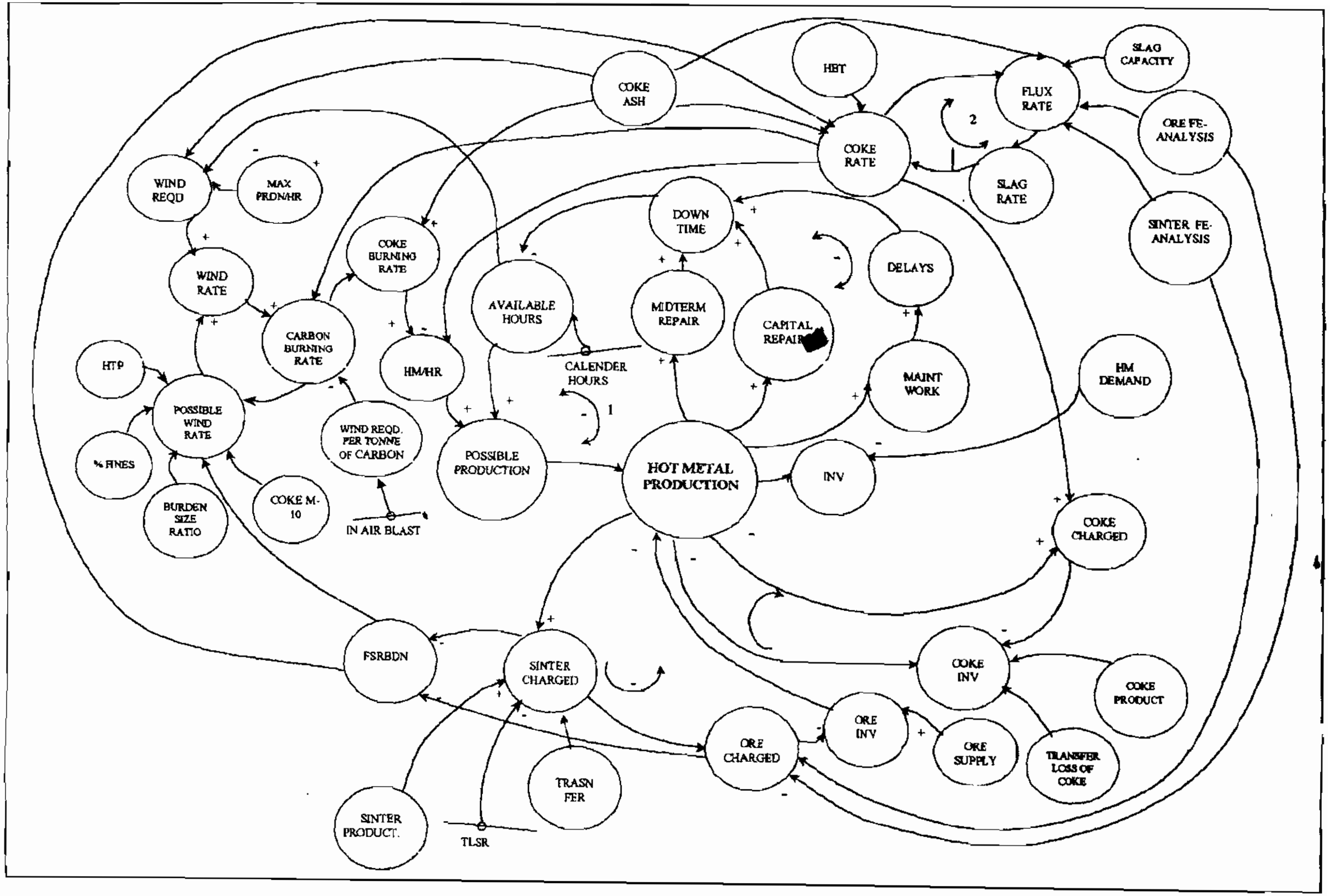

COKE ASH
HBT
FLUX RATE
SLAG CAPACITY
ORE FE-ANALYSIS
COKE RATE
2
SLAG RATE
SINTER FE-ANALYSIS
WIND REQD
MAX PRDN/HR
COKE BURNING RATE
DOWN TIME
DELAYS
WIND RATE
AVAILABLE HOURS
MIDTERM REPAIR
CAPITAL REPAIR
CARBON BURNING RATE
HM/HR
CALENDER HOURS
MAINT WORK
HM DEMAND
HTP
1
POSSIBLE WIND RATE
WIND REQD. PER TONNE OF CARBON
POSSIBLE PRODUCTION
HOT METAL PRODUCTION
INV
% FINES
COKE M-10
IN AIR BLAST
COKE CHARGED
BURDEN SIZE RATIO
FSRBDN
SINTER CHARGED
COKE INV
COKE PRODUCT
ORE INV
ORE CHARGED
ORE SUPPLY
TRANSFER LOSS OF COKE
TRASN FER
SINTER PRODUCT.
TLSR

FIGURE 3

5. Computer Implementation and Validation

After quantification of the individual relations based on historical data analysis perception of blast furnace operators and metallurgists, a computerised model has been developed with over 600 dynamo equations. The model consists of 39 level variables, 210 rate and auxiliary variables, and 33 parameters. After all these interdependencies have been built into DYNAMO equations, the model was validated with three years' data (April 1995-March 1998) for the blast furnaces of a major steel-making plant in Southeast Asia. We have considered 37 points of data. We used software called PC/DYNAMO (developed by Pugh Roberts Associates). After the output file is obtained in PC/DYNAMO, we have transformed the data-file to an Excel spreadsheet and drawn the graphs.

For validating the model, trend and pattern of modeled variables were studied against actual. We have considered the following variables for validation:

1. Monthly production of hot metal
2. Accumulated production of hot metal (accumulated over a period)
3. Net works cost
4. Works cost per ton

We have multiplied all the real and simulated values by a factor to maintain confidentiality of the cost and financial figures.

Figure 4 shows simulated yearly cumulative production of hot metal against yearly actual cumulative hot metal production. We find that simulated yearly cumulative

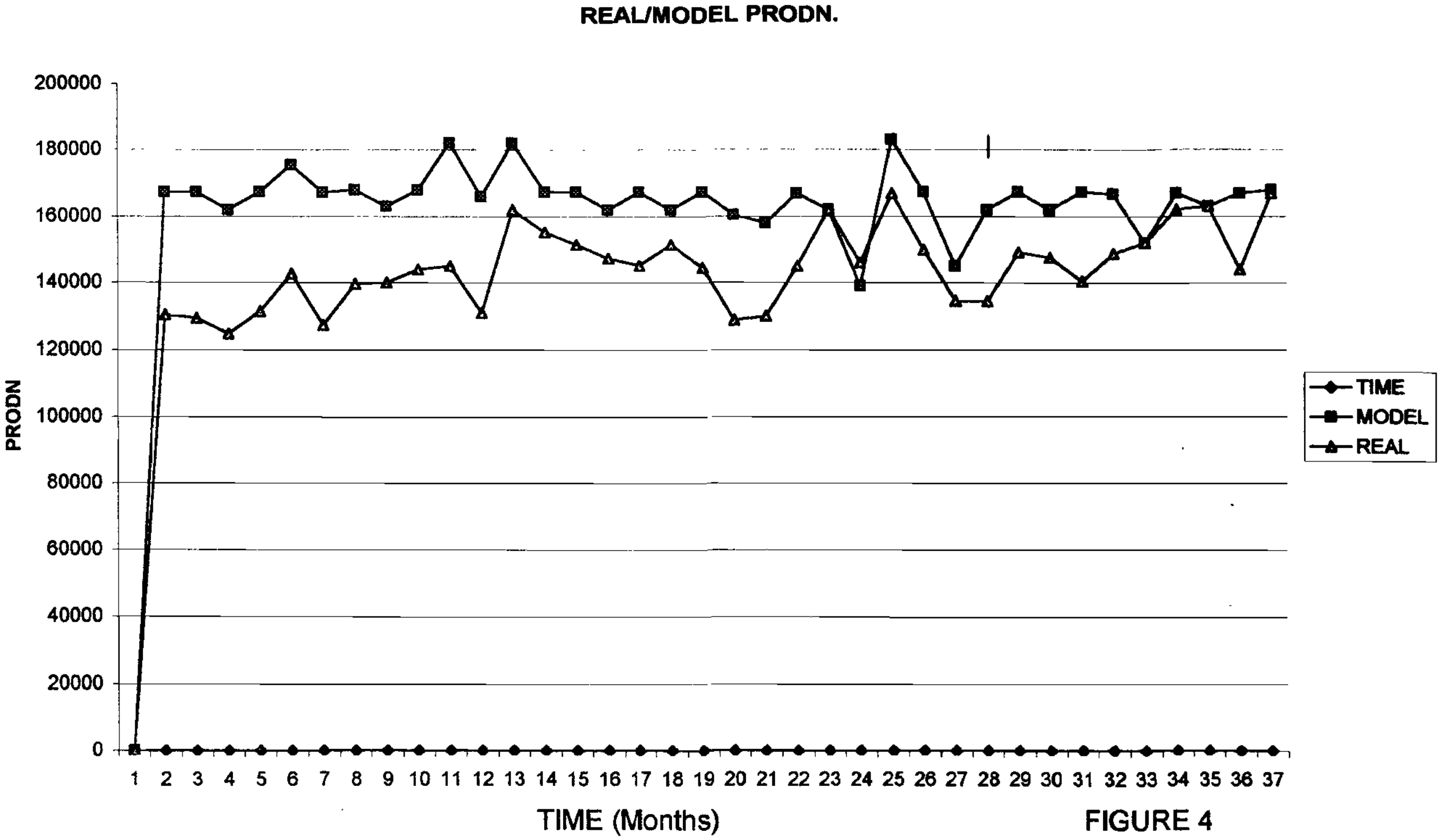

REAL/MODEL PRODN.
PRODN
200000
180000
160000
140000
120000
100000
80000
60000
40000
20000
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
TIME (Months)
TIME
MODEL
REAL

FIGURE 4

production follows the same trend as actual yearly cumulative production. We also find that the difference between simulated accumulated production and real accumulated production is decreasing over every year. This indicates that on an overall basis, the simulated cumulative production of hot metal is a good replication of the actual cumulative production behavior in the blast furnace.

After validating the yearly-accumulated figure, we now concentrate on actual monthly production over a period of 36 months. In Figure 5 we find that out of 36 points, 22 crests and troughs match with each other for simulated and actual monthly production. However, 3 of the crests and troughs do not match. In the first year (first 12 points of data) the difference between actual and simulated monthly production is significant. However, this difference reduces over the next two years.

In Figure 6, we show the simulated and actual values of net works cost (at the blast furnace). In this figure, the modeled values are excellent replication of real values. We find that out of 36 points, 28 crests and troughs match and 2 do not match. We also find that the simulated net works cost is lower than the actual net works cost.

In Figure 7, we show the simulated and real values of works cost per ton of hot metal production at the blast furnace. Owing to inflationary pressures on the prices of raw materials and increasing labor cost over 36 months period, the works cost per ton of hot metal has increased from RS 600/ton to 900/ton. The simulated value also shows the same

YEARLY CUMULATIVE PRODUCTION

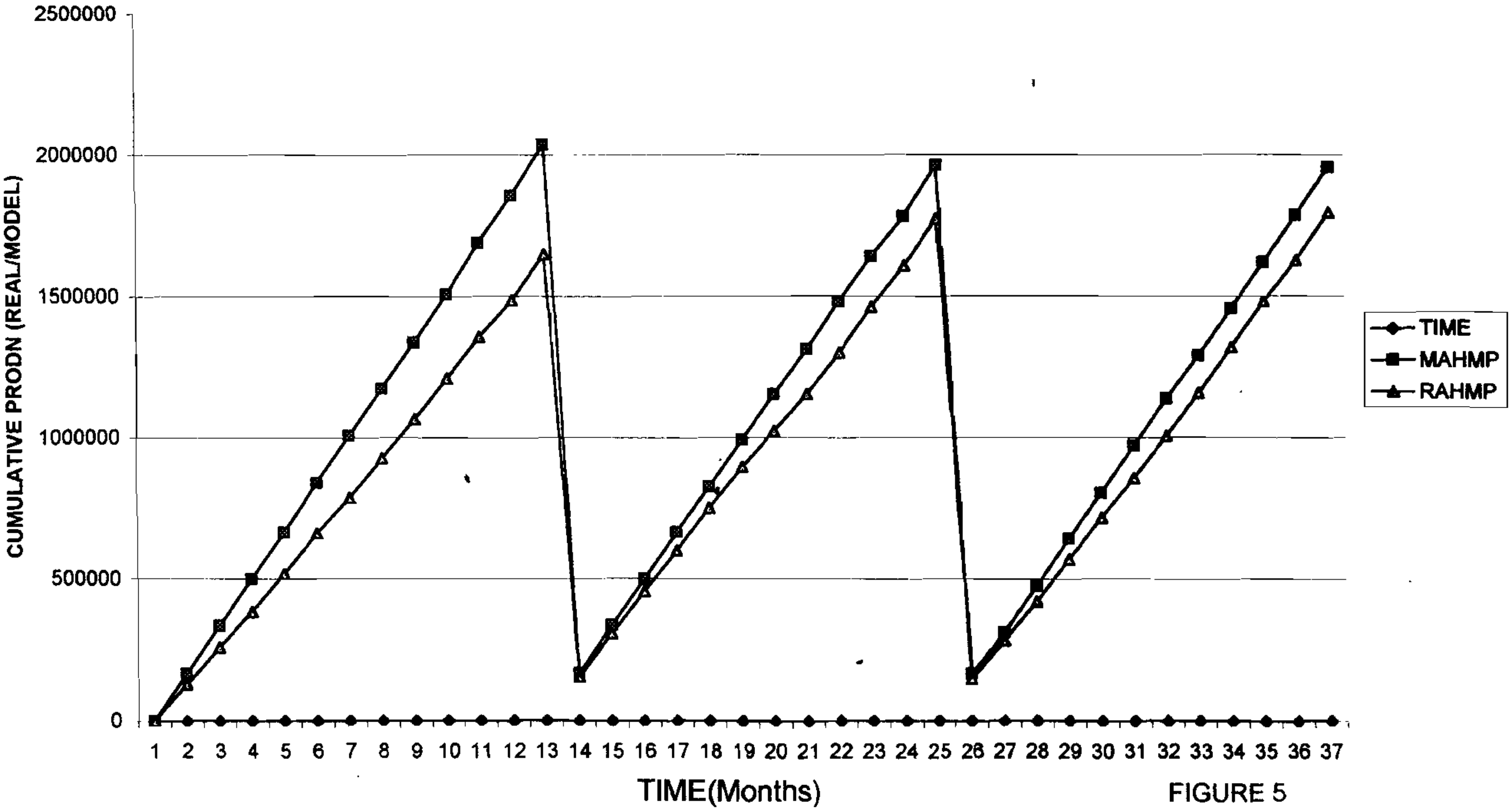


FIGURE 5

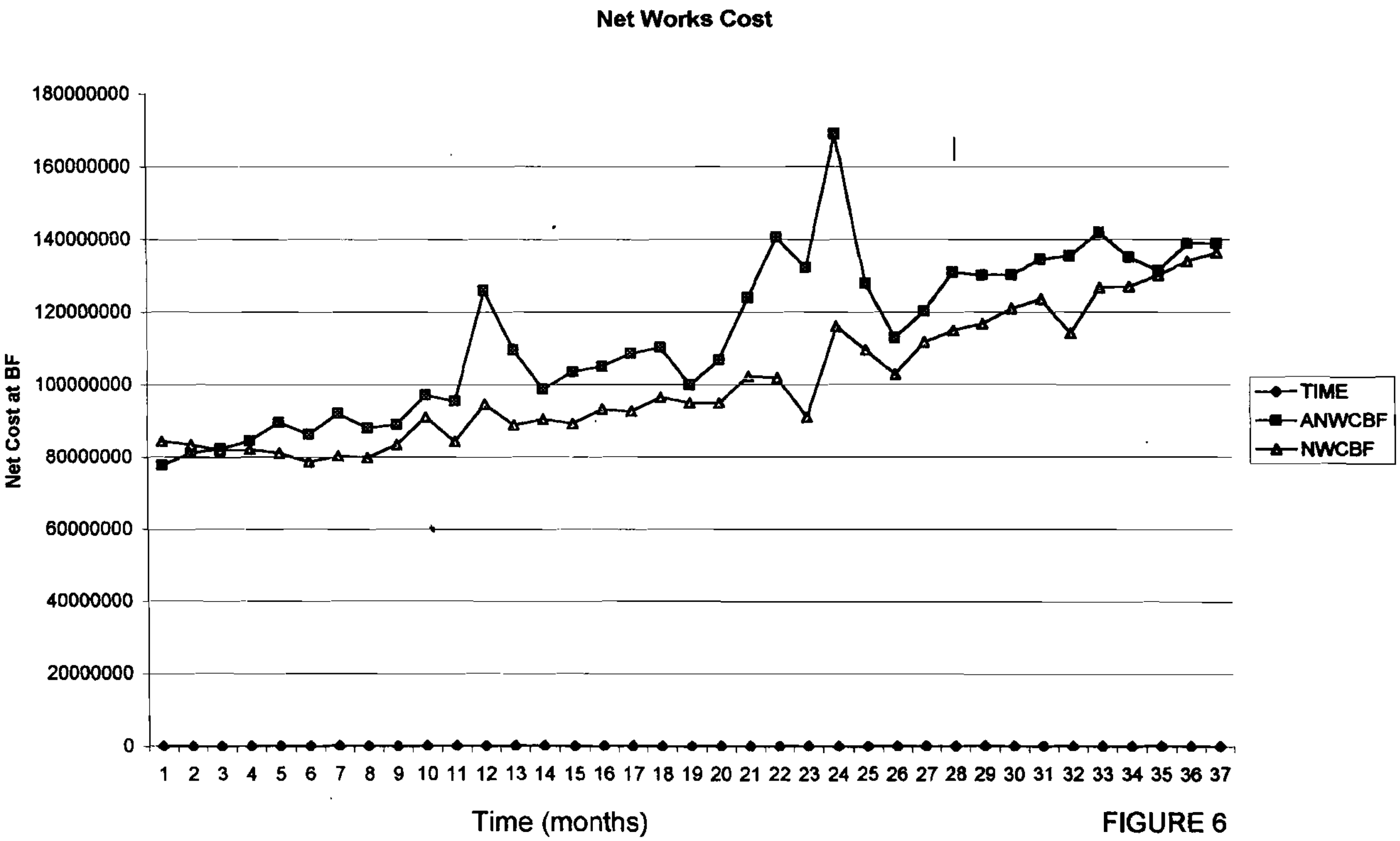

Net Works Cost
Net Cost at BF
180000000
160000000
140000000
120000000
100000000
80000000
60000000
40000000
20000000
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
Time (months)
TIME
ANWCBF
NWCBF

FIGURE 6

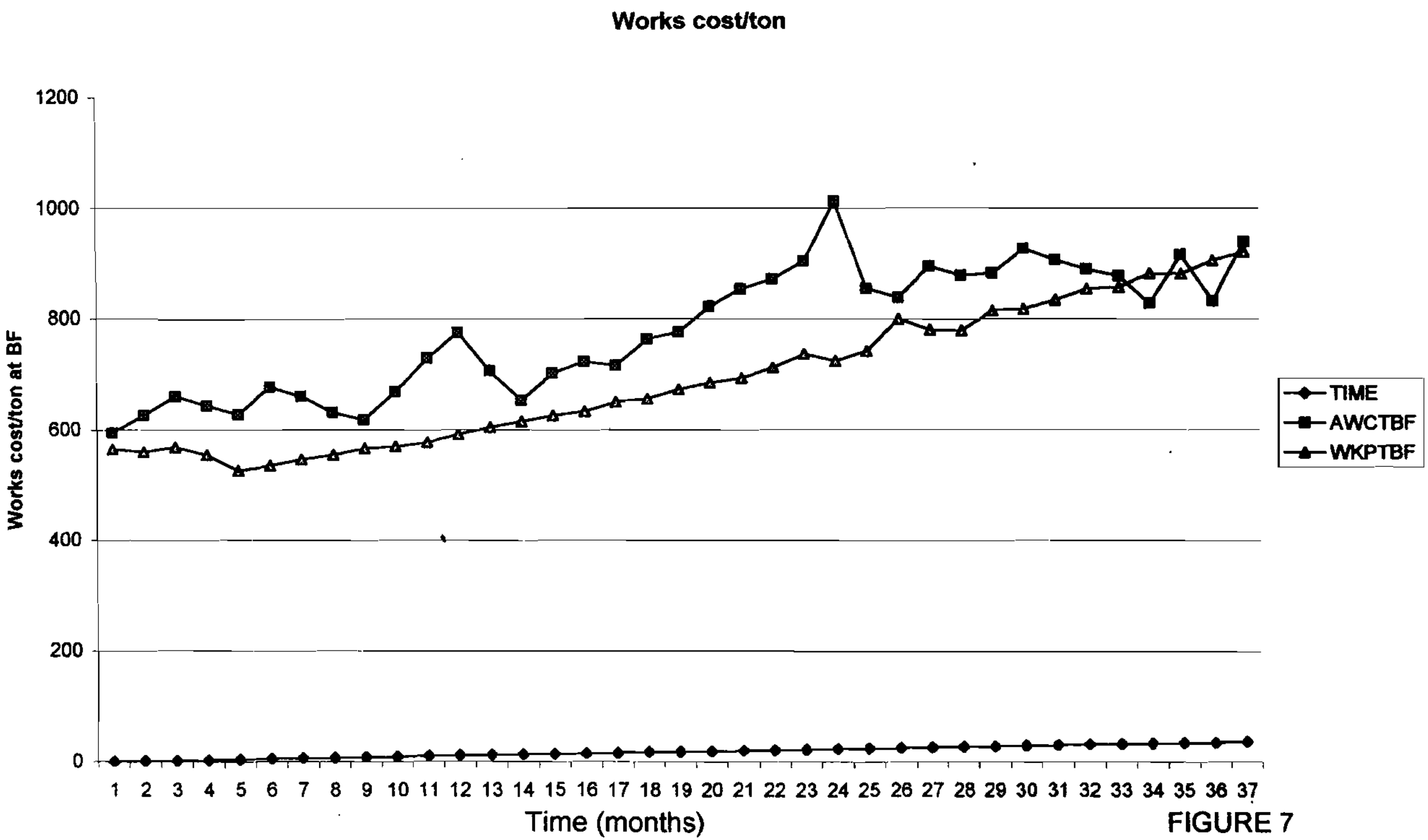

Works cost/ton
Works cost/ton at BF
1200
1000
800
600
400
200
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
Time (months)
TIME
AWCTBF
WKPTBF

FIGURE 7

trend in the inflationary pressure. However, the crests and troughs in this figure do not match.

For all the four variables, we have computed R^2 of actual and simulated values. This is shown in Table 1 along with t statistics and F statistics. t statistics and F statistics are computed between actual and modelled values. We assumed the Null hypothesis that there was no difference between actual and predicted values. The alternate hypothesis assumed that that there was a difference between actual and predicted values.

Table 1

Variables	R^2	t-statistics	F statistics
Production	0.8437	0.006647	0.15547
Acc. Production	0.8437	0.001915	0.65603
Works Cost	0.8537	0.2794	0.4260
Works cost per ton	0.9934	0.2543	0.6687
t-critical	2.72		
F-critical	1.55		

6. Conclusion

We have discussed in this paper a mathematical tool that can be used for simulating the operation of blast furnace for project evaluation. This model can be extended in the following direction

1. An integrated raw materials model involving the blast furnaces, coke ovens, sinter plants and lime making plant
2. An integrated model of raw materials of a company having multiple plants in different locations.

7. References

Dangerfield, B. (1993); A Systems Modelling Perspective On The Scale Effects In The Industry; *International Journal of Technology Management, Special Issue on "Manufacturing Technology*, Vol. 8, Nos. 3/4/5, pp. 371-383.

Fabian, T., 1958. "A Linear Programming Model of Integrated Iron and Steel Production", *Management Science*, Vol.4, pp. 415-49.

Fabian T. 1967, "Blast Furnace Production Planning - A Linear Programming Example," *Management Science* Vol. 14 pp. B1-B27.

Forrester, J.W., 1964. *Industrial Dynamics*, Cambridge, Massachusetts, MIT Press.

Fukuo, A.; Ifaya, H.; Yamana, S.; Nigo, S.; and Imatoni, N. 1983. "A Selection System of Optimal Operating Condition of a Blast Furnace," *Ironmaking Proceedings*, pp. 405-10.

Lankford, W.T.; Samways, N.L.; Craven, R.F.; and Macganon, H. E., 1985. *Making, Shaping and Treating of Steel*, Pittsburgh, U.S Steel Corporation, pp. 539-90.

Narchal, R. M. (1988); A Simulation Model for Corporate Planning in a Steel Plant; European Journal of Operational Research (Netherlands), Vol. 34(3), pp. 282-296.

Oaknock, T.W.; Pratt, H.R.; Thompson, J.E.; and White, D.G. 1983. "Utilisation of Daily Material and Energy Balance Programme to Evaluate and Improve Blast Furnace Performance," *Ironmaking Proceedings*, pp. 427-37.

Perez, L. and Hanikar, G. 1983. "Application of Computers for Blast Furnace Control," *Ironmaking Proceedings*, pp. 437-45.

Richestts, J.A., 1984. "Statistical Process Control in Iron Production: Development of Blast Furnace Operating Guidelines," *Ironmaking Proceedings*, pp. 439-48.

Savas, E.S. 1961. "An Approach to Computer Control of Blast Furnace, *Control System Technical Report No.4*, IBM Corporation.

Sinha G.P. and Dutta G. 1985 "A System Dynamic Model of a Blast Furnace for Project Evaluation" Proceedings of International Conference of System Dynamic Society, Nebraska, Lincoln, USA, pp. 838-51.

Sweeney, D. J. and Roppol L. E., 1983. "Development of a Burden Calculator," *Ironmaking Proceedings*, pp. 549-53.