

Modelling and Analysis of Production System of A Steel Plant- A System Dynamics Approach

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Abstract

In the fast changing economic scenario world over, the economic strength of any organization depends on the management's ability in improving quality, cutting production costs and providing better customer services to compete effectively in the global market. Even though every management aims at improving the productivity, there is a limitation on the part of various production facilities located in any plant as they cannot be stretched beyond a point. However, management can exploit the existing facilities to the maximum extent possible by introducing the latest state of art technology. Against this backdrop, present production scenario at Visakhapatnam Steel Plant (VSP) is described. The key variables considered for the simulation of steel plant production activities are: production of hot metal, liquid steel, prime blooms, bar mill products and wire rod products over a period of 20 years from 1994-2013. The results obtained from the SD modeling are validated. Further, the model is utilized to explore alternative policies, which have been compared for their relative effectiveness.

1. Introduction

A local Steel Plant has started its commercial production (integrated operations) in August 1992 and has been producing pig iron, blooms, billets, bar products, Wire Rod Mill (WRM) products and Medium Merchant and Structural Mill (MMSM) products. Ever since, it started production the plant has achieved rated capacity levels in a short time. In order to sustain and maintain a reasonable rate of growth, the management has plans to gradually reduce its manufacturing costs, improve overall productivity by introducing latest state of the art technology and to maintain inventory of raw materials and spare parts at minimum levels.

The plant was originally designed to produce 3.4Mtpa of Liquid Steel. Consequently, its capacity is reduced to 3 Mtpa due to paucity of funds. However, the facilities up to Blast Furnace were retained to produce 3.4Mt of Liquid Steel as per the original plan. The steel plant is now operating at production rates of about 4.15Mt of Hot Metal, 3.6Mt of Liquid Steel and 3.2Mt of Saleable Steel per annum representing capacity utilization levels of 122%, 120% and 122% respectively. The blast furnaces are capable of producing up to 5 Mt of hot metal with the adoption of modern techniques. At present, the steel making capacity is the bottleneck with an installed capacity of about 3Mt per year and it can not be enhanced beyond 125% of the rated capacity.

2. Objectives

The main focus of the study is:

(i) to improve overall productivity on a continuous basis by exploiting the full potential of the existing units

(ii) to optimize the product mix

(iii) to upgrade and modify the existing technology to enhance the production with minimum investment and

(iv) to add new production capacities wherever required to meet the demand for company's products.

3. Model description:

As the steel production capacity is crucial in the entire production run, it is taken as the goal. Backward integration of inputs to SMS converter i.e., the hot metal, and other inputs and forward integration of the outputs from SMS converter i.e., liquid steel and down stream products have been done. Further, inputs to the blast furnace are integrated with the hot metal requirements and the inputs to base mix are integrated with the sinter requirement. These are evident from the equations that follow.

Fig. 1 depicts the causal loop diagram and Figs 2 to 6 represent flow diagram of the production sub-sector. An attempt is made here to capture the production processes in detail so that the model can become a replica of reality. The operations of a steel plant right from production of coke and hot metal to liquid steel and rolled products are dependent mutually and the said flow diagram brings out backward and forward integration of manufacturing processes involved in the steel plant. The base model is developed so that experiments for what- if- then situations can be carried out even by the plant managers and to find out likely scenarios. Such experiments are only carried out here as part of the policy analysis and testing. The results are also useful to that extent.

The procedure for system dynamic simulation of the production sub-sector is described by the following equations and serves as the base model for portraying the behavior of production activities of the plant under study.

The various stages in the production of liquid steel and down stream products are divided in to five stages. They are: (i) production of BF grade Coke (ii) Sinter (iii) Hot metal (iv) liquid steel and (v) down stream products. For production of BF grade Coke, Coking Coal is required. Sinter requires Coke Breeze, Iron ore fines, Manganese ore fines, Sand and Quartzite fines, BF grade Lime stone fines and BF grade Dolomite fines. Production of Hot metal requires Sinter, BF grade Dolomite, BF grade Lime stone and Quartzite. Hot metal, SMS grade Lime stone, SMS grade Dolomite, Scrap and Ferro-alloys are required for production of Liquid Steel. All these raw materials in the pipeline

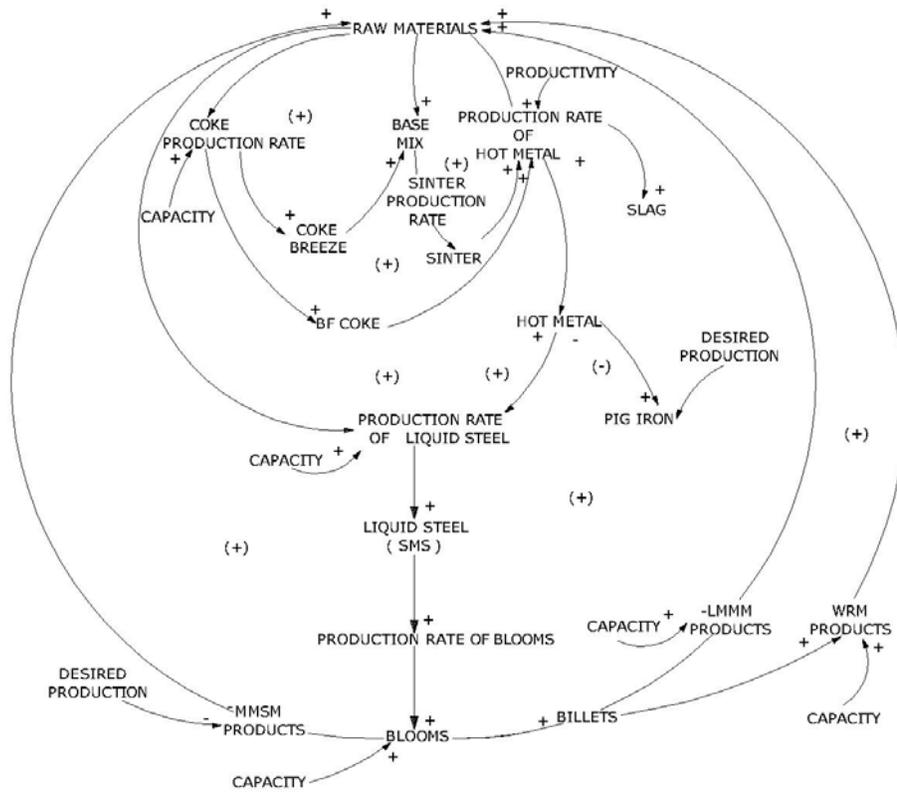


fig1 :CASUAL LOOP DIAGRAM FOR PRODUCTION SUBSYSTEM

are defined as third order delay level variables as explained below. In Fig 2, flow diagram for raw material receipts Coking coal and production of base mix are shown.

3.1 Raw materials in the pipeline:

- a) Coking Coal in pipeline is defined as a third order delay function and is given by the following equation:

$$COALIP = COALIP + DT * (COALOR - COLCOR)$$

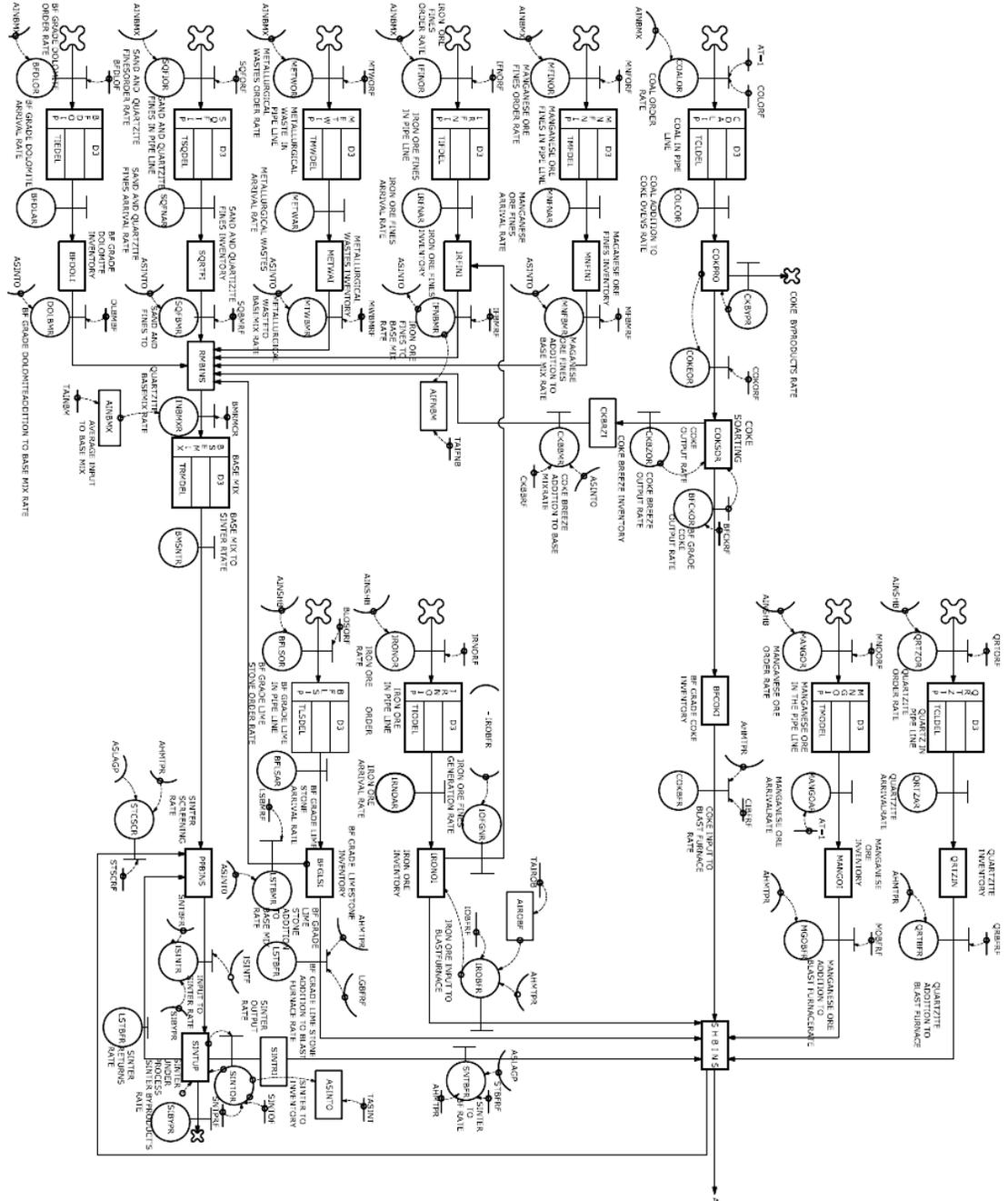
where COALIP = Coking Coal in pipeline

COALOR = Coking Coal order rate/annum

COLCOR = Coking Coal addition to Coke ovens rate/annum

- b) Coking Coal order rate is defined as the discrepancy between coal order and coal inventory and is given below:

Fig 2 : flow diagram of hot metal production



$$\text{COALOR} = \text{COKEOR} * \text{COLORF}$$

where COALOR = Coking Coal order rate/annum

- c) Coking Coal addition to Coke ovens rate (COLCOR) is defined as a Call Delay Function and is given below:

$$\text{CALL DELAY} (\text{CLORRI}, \text{COALOR}, \text{R1}, \text{R2}, \text{COLCOR}, \text{TCLDEL})$$

where CLORRI = Coking Coal order rate, initial

COALOR = Coking Coal order rate/annum

R1, R2 = Delay Constants

COLCOR = Coking Coal arrival rate/annum

TCLDEL = Time delay to adjust order rate, a constant

In the similar way Manganese ore fines in the pipeline (MNFNIP), Iron ore fines in the pipeline (IRFNIP), Metallurgical wastes in the pipeline (METWIP), Sand and quartzite fines (SQFIIP), BF grade dolomite in the pipe line (BFDOIP), Iron ore in pipeline (IRNOIP), BF grade lime stone in pipe line (BFLSIP), Quartzite in pipeline (QRTZIP), Manganese ore in the pipe line (MNGOIP), SMS grade Dolomite in the pipeline (SMDLIP), Scrap order in the pipe line (SCRPIP), Ferro-alloys in pipe line (FERAIP), SMS lime stone inventory in the pipeline (SMLSIP) are also defined as a third order delay levels as explained above.

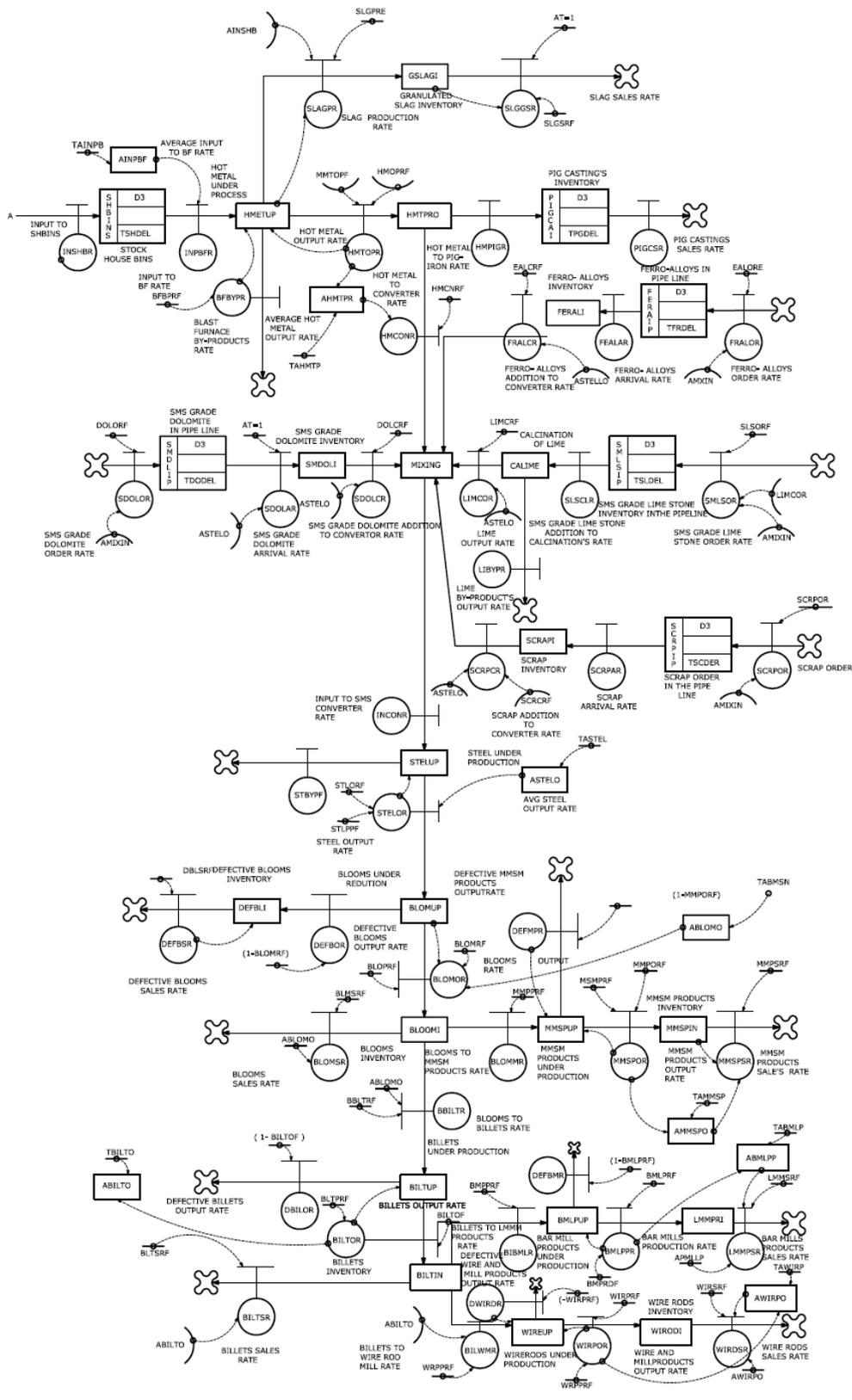


fig3 : flow diagram of steel production

3.2 Production of BF grade Coke:

Coking Coal is processed in Coke ovens to produce Metallurgical Coke. Then it is sorted out in to B F grade Coke and Coke Breeze. The related equations are explained below.

- i) a) Coke processing (COKPRO) in coke ovens is defined as a level equation and is given below:

$$COKPRO = COKPRO + DT * (COLCOR - (COKEOR + CKBYPR))$$

where COKPRO = Coke processing in coke ovens

COLCOR = Coking Coal input to coke ovens rate/annum

COKEOR = Coke output Rate per.annum

CKBYPR = Coke ovens by-products rate/annum

- b) Coke by-products output rate (CKBYPR) is defined as a rate equation and given by:

$$CKBYPR = COKPRO * (1 - COKORF)$$

where COKPRO = Coke processing in coke ovens

COKORF = Coke output from coke ovens rate fraction, a constant

- ii) a) Coke sorting (COKSOR) is defined as a level equation and is give below:

$$COKSOR = COKSOR + DT * (COKEOR - (BFCKOR + CKBZOR))$$

where COKSOR = Coke sorting

COKEOR = Coke output rate

BFCKOR = BF grade coke output rate

CKBZOR = Coke breeze output rate

- b) BF grade coke output rate (BFCKOR) is defined as a rate equation and is give by:

$$BFCKOR = COKSOR * BFCKRF$$

where COKSOR = Coke sorting

BFCKRF = BF grade coke output rate fraction, a constant

- c) Coke breeze output rate (CKBZOR) is defined as a rate equation and is given below as:

$$CKBZOR = COKSOR * (1 - BFCKRF)$$

- iii) a) BF grade coke inventory (BFCOKI) is defined as a level equation and is given below:

$$BFCOKI = BFCOKI + DT * (BFCKOR - COKBFR)$$

where BFCOKI = BF grade coke inventory
 BFCKOR = BF grade coke output rate
 COKBFR = Coke input to blast furnace rate

- b) Coke input to blast furnace rate (COKBFR) is defined as rate equation and is given below:

$$COKBFR = AHMTPR * CIBFRF$$

where AHMTPR = Average Hot metal output rate/annum
 CIBFRF = Coke input to blast furnace rate factor, a constant.

- iv) a) Coke breeze inventory (CKBRZI) is defined as a level equation and is given below:

$$CKBRZI = CKBRZI + DT * (CKBZOR - CKBBMR)$$

where CKBZOR = Coke breeze output rate
 CKBBMR = Coke breeze to base mix rate

- b) Coke breeze output rate (CKBZOR) is defined as a rate equation and is given below:

$$CKBZOR = COKSOR * (1 - BFCKRF)$$

- c) Coke breeze addition to base mix rate is defined as a rate equation and is given below:

$$CKBBMR = ASINTO * CKBBRF$$

where ASINTO = Average Sinter output rate
 CKBBRF = Coke breeze addition to base mix rate factor, a constant

3.3 Inventory of raw materials:

All the raw materials required are procured from various sources including foreign countries. Hence the company maintains inventory of all raw materials which last approximately for a period of 45 days. The inventories of various raw materials are expressed as level variables and are explained below.

- i) a) Iron ore inventory (IRONOI) is defined as a level equation and is given below:

$$IRONOI = IRONOI + DT * (IRNOAR - (IROBFR + IOFGNR))$$

where IRNOAR = Iron ore arrival rate/annum
 IROBFR = Iron ore input to blast furnace rate/annum
 IOFGNR = Iron ore fines generation rate/annum

- b) Iron ore input to blast furnace rate (IROBFR) is defined as a rate equation and is given below:

$$IROBFR = AHMTPR * IOBFRF$$

where IOBFRF = Iron ore addition to blast furnace rate factor, a constant

- c) Iron ore fines generation rate (IOFGNR) is defined as a rate equation and is given below:

$$\text{IOFGNR} = (\text{IRONOI}/\text{AT} - \text{IROBFR})$$

where IRONOI = Iron ore inventory

AT = Adjustment time

IROBFR = Iron ore input to blast furnace rate

Similarly inventories of BF grade lime stone (BFGLSI), Manganese ore fines (MNFINI), Iron ore fines (IRFINI), Metallurgical wastes (METWAI), Sand and quartzite fines (SQRTFI), BF grade dolomite (BFDOLI), Quartzite (QRTZIN), Manganese ore (MANGOI) are defined as a level equations as explained above.

3.4 Production of Base Mix:

Base Mix is made up of Coke Breeze, Manganese ore fines, Iron ore fines, Metallurgical wastes, Sand and quartzite fines, Dolomite fines and BF grade Limestone fines. Base Mix is used to produce Sinter as indicated in Fig 3. The related equations are explained below.

- i) a) Base mix (BSEMIX) is defined as a level variable and is given below:

$$\text{BSEMIX} = \text{BSEMIX} + \text{DT} * (\text{INRMBR} - \text{BMSNTR})$$

where INRMBR = Input to base mix rate

BMSNTR = Base mix to sinter rate

- b) Input to base mix rate (INRMBR) is defined as a rate variable and is obtained by adding Coke Breeze, Manganese ore fines, Iron ore fines, Metallurgical wastes, Sand and quartzite fines, Dolomite fines and BF grade Limestone fines and is given as:

$$\text{INRMBR} = (\text{CKBBMR} + \text{MNF BMR} + \text{IFNBMR} + \text{MTWBMR} + \text{SQFBMR} + \text{DOLBMR} + \text{LSTBMR}) * \text{BMRMCF}$$

- c) Base mix to sinter rate (BMSNTR) is defined as a rate equation and is obtained from the following call Delay functions:

$$\text{CALL DELAY} (\text{INBSTE}, \text{BMSNTR}, \text{R29}, \text{R30}, \text{ISINTR}, \text{TRMDEL})$$

- ii) a) Sinter under process (SINTUP) is defined as a level equation and is given below:

$$\text{SINTUP} = \text{SINTUP} + \text{DT} * (\text{ISINTR} - (\text{SINTOR} + \text{SIBYPR}))$$

SNTBFR = Sinter to BF rate = (AHMTPR + ASLAGP) * STBFRF

SIBYPR = Sinter By-products production rate

SINTRR = Sinter returns rate

- b) Sinter returns from sinter rate (SINTRR) is defined as a rate equation and is given below:

$$\text{SINTRR} = \text{SINTOR} - \text{SNTBFR}$$

- iii) a) Sinter inventory (SINTRI) is defined as a level equation and is given below by:

$$\text{SINTRI} = \text{SINTRI} + \text{DT} * (\text{SINTOR} - \text{SNTBFR})$$

where SINTOR = Sinter output from sintering process

SNTBFR = Sinter addition to blasé furnace rate

- b) Sinter addition to blasé furnace rate (SNTBFR) is defined as a rate equation and is given by:

$$\text{SNTBFR} = (\text{AHMTPR} + \text{ASLAGP}) * \text{STBFRF}$$

where STBFRF = Sinter addition to blast furnace rate factor, a constant

3.5 Production of Hot Metal:

Iron ore, BF grade lime stone, BF grade lime stone, B F grade Quartzite, Metallurgical Coke and Sinter are added to Blast Furnace so as to produce Hot Metal as indicated in Fig 4. Production of Hot metal is defined as a level variable and the related equations are explained below:

- i) a) Hot metal under process (HMETUP) is defined as a level equation and is given below:

$$\text{HMETUP} = \text{HMETUP} + \text{DT} * (\text{INPBFR} - (\text{HMTOPR} + \text{SLAGPR} + \text{BFBYPR}))$$

where INPBFR = Input to blast furnace rate/annum

HMTOPR = Hot metal output rate/annum

SLAGPR = Slag production rate/annum

BFBYPR = Blast furnace by-products rate/annum

- b) Input to blast furnace rate(INPBFR) is defined as a rate variable and is given below:

$$\text{INPBFR} = \text{IROBFR} + \text{LSTBFR} + \text{QRTBFR} + \text{MGOBFR} + \text{COKBFR} + \text{SNTBFR}$$

- c) Hot metal output rate (HMTOPR) is defined as a rate variable and is given below:

$$\text{HMTOPR} = \text{HMETUP} * \text{HMTOPF} * \text{HMOPRF}$$

where HMTOPF= Hot metal productivity factor

HMOPRF = Hot metal production rate factor, a constant

- d) Slag production rate (SLAGPR) is defined as a rate variable and is given below:

$$\text{SLAGPR} = \text{HMETUP} * \text{SLGPRF}$$

where SLGPRF = Slag production rate factor, a constant

- e) Blast furnace by-products production rate (BFBYPR) is defined as a rate equation as given below:

$$\text{BFBYPR} = (\text{INRBFR} - (\text{HMTOPR} + \text{SLAGPR})) * \text{BFBPRF}$$

where BFBPRF = Blast furnace by-products production rate factor, a constant

34. a) Hot metal produced (HMTPRO) is defined as a level equation and is given below:

$$\text{HMTPRO} = \text{HMTPRO} + \text{DT} * (\text{HMTOPR} - (\text{HMCONR} + \text{HMPIGR}))$$

where HMTOPR = Hot metal output rate/annum

HMCONR = Hot metal to converter rate/annum

HMPIGR = Hot metal to pig iron rate/annum

- b) Hot metal to converter rate (HMCONR) is defined as a rate equation and is given below:

$$\text{HMCONR} = \text{AHMTPR} * \text{HMCNRF}$$

where HMCNRF = Hot metal to converter rate factor, a constant

- c) Hot metal to pig iron rate (HMPIGR) is defined as a rate equation and is given below:

$$\text{HMPIGR} = (\text{AHMTPR} - \text{HMCONR})$$

35. a) Granulated slag inventory is defined as a level variable as is given below:

$$\text{GSLAGI} = \text{GSLAGI} + \text{DT} * (\text{SLAGPR} - \text{SLAGSR})$$

where SLAGPR = Slag production rate/annum

SLAGSR = Slag sales rate/annum

- b) Slag production rate (SLAGPR) is defined as a rate equation and is given below:

$$\text{SLAGPR} = \text{HMETUP} * \text{SLGPRF}$$

where SLGPRF = Slag production rate factor, a constant

- c) Slag sales rate (SLAGSR) is defined as a rate equation and is given below:

$$\text{SLAGSR} = \text{GSLAGI} * \text{SLGSRF}$$

where SLGSRF = Slag sales rate factor, a constant

36. a) Pig casting under production (PIGCUP) is defined as a level variable and is given:

$$\text{PIGCUP} = \text{PIGCUP} + \text{DT} * (\text{HMPIGR} - \text{PIGCPR})$$

where HMPIGR = Hot metal to pig iron rate/annum

PIGCPR = Pig casting production rate/annum

- b) Pig castings production rate (PIGCPR) is defined as a rate equation and is given below:

$$\text{PIGCPR} = \text{PIGCUP} * \text{PGCPRF}$$

where PGCPRF = Pig castings production rate factor, a constant

37. a) Pig castings inventory (PIGCAI) is defined as a level equation and is given below:

$$\text{PIGCAI} = \text{PIGCAI} + \text{DT} * (\text{HMPIGR} - \text{PIGCSR})$$

where PIGCPR = Pig castings production rate/annum

PIGCSR = Pig castings sales rate/annum

b) Pig castings sales rate (PIGCSR) is defined as a rate equation and is given below:

$$\text{PIGCSR} = \text{PIGCAI} * \text{PGCSRF}$$

where PGCSRF = Pig castings sales rate factor, a constant

3.6 Production of Liquid Steel:

Production of Liquid Steel requires Hot metal, SMS grade calcined lime, Ferro alloys, Scrap and SMS grade Dolomite and are processed in Steel Melt Shop using Convertors as indicated in Fig. 5 and the related equations are explained below.

i) a) Calcination of lime (CALIME) is defined as a level variable and is given below:

$$\text{CALIME} = \text{CALIME} + \text{DT} * (\text{SLSCLR} - (\text{LIMCOR} + \text{LIBYPR}))$$

where SLSCLR = SMS grade lime stone addition to calcinations rate

LIMCOR = Lime output rate/annum

LIBYPR = Lime by-products output rate/annum

b) Lime addition to converter rate (LIMCOR) is defined as a rate variable as given below:

$$\text{LIMCOR} = \text{ASTELO} * \text{LIMCRF}$$

LIMCRF = Lime addition to converter rate factor, a constant

LIBYPR = Lime by-product rate and is given by the following equation:

$$\text{LIBYPR} = (\text{ASLSCLR} - \text{ALIMCO})$$

ii) a) Ferro-alloys inventory (FERALI) is defined as a level variable and is given below:

$$\text{FERALI} = \text{FERALI} + \text{DT} * (\text{FEALAR} - \text{FRALCR})$$

where FEALAR = Ferro-alloys arrival rate/annum

FRALCR = Ferro-alloys addition to converter rate/annum

b) Ferro-alloys addition to converter rate (FRALCR) is defined as a rate equation and is given below:

$$\text{FRALCR} = \text{ASTELO} * \text{FALCRF}$$

where FALCRF = Ferro-alloys addition to converter rate factor, a constant

iii) a) Scrap inventory (SCRAPI) at present is defined as a level variable and is given by the following equation.

$$\text{SCRAPI} = \text{SCRAPI} + \text{DT} * (\text{SCRPAR} - \text{SCRPCR})$$

where SCRPAR = Scrap arrival rate/annum

SCRPCR = Scrap addition to converter rate/annum

b) Scrap addition to converter rate (SCRPCR) is defined as a rate variable and is given by the following equation.

$$\text{SCRPCR} = \text{ASTELO} * \text{SCRCRF}$$

where SCRCRF = Scrap addition to converter rate factor, a constant

- iv) a) SMS grade Dolomite inventory (SMDOLI) is defined as a level variable and is given by the following equation.

$$SMDOLI = SMDOLI + DT * (SDOLAR - SDOLCR)$$

where SDOLAR = SMS grade Dolomite arrival rate/annum

SDOLCR = SMS grade Dolomite addition to converter rate/annum

- b) SMS grade Dolomite addition to converter rate (SDOLCR) is defined as rate variable and is given by the following equation.

$$SDOLCR = ASTELO * DOLCRF$$

where DOLCRF = Dolomite addition to converter rate factor, a constant

- v) Hot metal, lime, ferro alloys, scrap, dolomite are mixed and then processed. Mixing (MIXING) of these materials is defined as a level equation and is explained below.

$$MIXING = MIXING + DT * (INMIXR - INCONR)$$

where INMIXR = (HMCONR + LIMCOR + FRALCR + SCRPCR + SDOLCR)

INCONR is obtained from the following Call Delay function:

CALL DELAY (INMXRI, INMIXR, R35, R36, INCONR, TINDEL)

- vi) a) Steel under production (STELUP) is defined as a level variable and is given by the following equation.

$$STELUP = STELUP + DT * (INCONR - (STELOR + STBYPR))$$

where INCONR = Inputs into converter rate/annum

STELOR = Steel output rate/annum

STBYPR = Steel by-products production rate/annum

- b) Steel output rate (STELOR) is defined as a rate variable and is given by the following equation.

$$STELOR = STELUP * STLORF * STLPPF$$

Where STLORF=Liquid steel production output rate factor

STLPPF=Liquid steel productivity factor

- c) Steel by-products production rate (STBYPR) is defined as a rate variable and given by the following equation.

$$STBYPR = STELUP * (1 - STLPRF)$$

3.7 Production of Semis and downstream products:

Liquid steel is converted in to Blooms. These are classified as prime blooms and defective blooms. Prime blooms are used for producing Billets and MMSM Products. The Billets are inturn used for producing LMMM Products and WRM products. Fig. 6 indicates these processes and related equtions are given below.

- i) a) Blooms under production (BLOMUP) is defined as a level variable and is given by the following equation.

$$\text{BLOMUP} = \text{BLOMUP} + \text{DT} * (\text{STELOR} - (\text{BLOMOR} + \text{DEFBOR}))$$
where BLOMOR = Blooms output rate/annum
DEFBOR = Defective Blooms output rate/annum
- b) Steel to Blooms rate (STLBLR) is defined as a rate variable and is given by the following equation.

$$\text{STLBLR} = \text{STLPRO} * \text{STLBLF}$$
- c) Blooms output rate (BLOMOR) is defined as a rate variable and is given by the following equation.

$$\text{BLOMOR} = \text{BLOMUP} * \text{BLOMRF} * \text{BLOPRF}$$
where BLOMRF = Blooms output rate factor, a constant
BLOPRF = Blooms productivity factor, a constant
- d) Defective blooms output rate (DEFBOR) is defined as a rate variable and is given by the following equation.

$$\text{DEFBOR} = \text{BLOMUP} * (1 - \text{BLOMRF})$$
- ii) a) Blooms inventory (BLOOMI) is defined as a level variable and is given by the equation:

$$\text{BLOOMI} = \text{BLOOMI} + \text{DT} * (\text{BLOMOR} - (\text{BLOMMR} + \text{BBILTR} + \text{BLOMSR}))$$
where BLOMOR = Blooms output rate/annum
BLOMMR = Blooms to MMSM products rate/annum
BBILTR = Blooms to billets rate/annum
BLOMSR = Blooms sales rate/annum
- b) Blooms to MMSM products rate (BLOMMR) is defined as a rate variable and given by the following equation.

$$\text{BLOMMR} = \text{ABLOMO} * \text{MMPPRF}$$
where BILMRF = Blooms to MMSM products rate factor, a constant
- c) Blooms to billets rate (BBILTR) is defined as a rate variable and is given by the equation:

$$\text{BBILTR} = \text{ABLOMO} * \text{BBLTRF}$$
where BBLTRF = Blooms to billets rate factor, a constant
- d) Blooms sales rate (BLOMSR) is defined as a rate variable and is given by the following equation:

$$\text{BLOMSR} = \text{ABLOMO} * \text{BLMSRF}$$
where BLMSRF = Blooms sales rate fraction, a constant

iii) a) MMSM products under production (MMSPUP) is defined as a level variable and is given by the following equation:

$$\text{MMSPUP} = \text{MMSPUP} + \text{DT} * (\text{BLOMMR} - (\text{MMSPOR} + \text{DEFMPR}))$$

where BLOMMR = Blooms to MMSM products production rate/annum

MMSPOR = MMSM products output rate/annum

DEFMPR = Defective MMSM products output rate/annum

b) MMSM products output rate (MMMPOR) is defined as a rate variable and is given by the following equation:

$$\text{MMSPOR} = \text{MMSPUP} * \text{MMPORF} * \text{MSMPRF}$$

where MMPORF = MMSM products production rate factor, a constant

MSMPRF = MMSM products productivity factor, a constant

c) Defective MMSM products output rate (DEFMPR) is defined as a rate equation and is given by the following equation:

$$\text{DEFMPR} = \text{MMSPUP} * (1 - \text{MMPORF})$$

iv) a) MMSM products inventory (MMSPIN) is defined as a level variable and is given by the following equation:

$$\text{MMSPIN} = \text{MMSPIN} + \text{DT} * (\text{MMSPOR} - \text{MMSPSR})$$

where MMSPOR = MMSM products output rate/annum

MMSPSR = MMSM products sales rate/annum

b) MMSM products sales rate (MMSPSR) is defined as rate variable and is given by the following equation:

$$\text{MMSPSR} = \text{AMMSPO} * \text{MMPSRF}$$

where MMPSRF = MMSM products sales rate factor, a constant

v) a) Billets under production (BILTUP) is defined as a level variable and is given by the following equation:

$$\text{BILTUP} = \text{BILTUP} + \text{DT} * (\text{BBILTR} - (\text{BILTOR} + \text{DBILOR}))$$

where BBILTR = Blooms to billets rate/annum

BILTOR = Billets output rate/annum

DBILOR = Defective billets output rate/annum

b) Billets output rate (BILTOR) is defined as a rate variable and is given by the following equation:

$$\text{BILTOR} = \text{BILTUP} * \text{BILTOF} * \text{BLTPRF}$$

where BILTOF = Billets output rate factor, a constant

BLTPRF = Billets productivity factor, a constant

c) Defective billets output rate (DBILOR) is defined as a rate variable and is given by the following equation:

$$\text{DBILOR} = \text{BILTUP} * (1 - \text{BILTOF})$$

vi) a) Billets inventory (BILTIN) is defined as a level variable and is given by the following equation:

$$\text{BILTIN} = \text{BILTIN} + \text{DT} * (\text{BILTOR} - (\text{BIBMLR} + \text{BILWMR} + \text{BILTSTR}))$$

where BILTOR = Billets output rate/annum

BIBMLR = Billets to LMMM products rate/annum

BILWMR = Billets to wire rod mill rate/annum

BILSTR = Billets sales rate/annum

- b) Billets to LMMM products rate (BLBMLR) is defined as a rate variable and is given by the following equation:

$$\text{BIBMLR} = \text{ABILTO} * \text{BMPPRF}$$
 where BIBMRF = Billets to LMMM products production rate factor, a constant
- c) Billets to wire rod mill rate (BILWMR) is defined as a rate variable and is given by the following equation:

$$\text{BILWMR} = \text{ABILTO} * \text{WRPPRF}$$
 where BILWRF = Billets to wire rod mill rate fraction, a constant
- d) Billets sales rate (BILTSTR) is defined as a rate variable and is given by the following equation.

$$\text{BILTSTR} = \text{ABILTO} * \text{BLTSRF}$$
 where BLTSRF = Billets sales rate factor, a constant
- vi) a) Bar rod mill products under production (BMLPUP) is defined as a level variable and is given by the following equation.

$$\text{BMLPUP} = \text{BMLPUP} + \text{DT} * (\text{BIBMLR} - (\text{BMLPPR} + \text{DEFBMR}))$$
 where BIBMLR = Billets to bar mill rate/annum
 BMLPPR = Bar mill products production rate/annum
 DEFBMR = Defective bar mill products output rate/annum
- b) Bar mill products production rate (BMLPPR) is defined as a rate variable and is given by the following equation:

$$\text{BMLPPR} = \text{BMLPUP} * \text{BMLPRF} * \text{BMPROF}$$
 where BMLPRF = Bar mill products production rate factor, a constant
 BMPROF = Bar mill products productivity factor, a constant
- c) Defective bar mill products output rate (DEFBMR) is defined as a rate variable and is given by the following equation.

$$\text{DEFBMR} = \text{BMLPUP} * (1 - \text{BMLPRF})$$
- vii) a) Bar mill products inventory (LMMPRI) is defined as a level variable and is given by the following equation:

$$\text{LMMPRI} = \text{LMMPRI} + \text{DT} * (\text{BMLPPR} - \text{LMMPSR})$$
 where BMLPPR = Bar mill products production rate/annum
 LMMPSR = Bar mill products sales rate/annum
- b) Bar mill products sales rate (LMMPSR) is defined as a rate variable and is given by the following equation.

$$\text{LMMP SR} = \text{ABMLPP} * \text{LMMSRF}$$

where LMMSRF = Barmill products sales rate factor, a constant

- viii) a) Wire rods under production (WIREUP) is defined as a level variable and is given by the following equation:

$$\text{WIREUP} = \text{WIREUP} + \text{DT} * (\text{BILWMR} - (\text{WIRPOR} + \text{DWIRPR}))$$

where BILWMR = Billets to wire rod mills rate/annum

WIRPOR = Wire rod mill products output rate/annum

DWIRPR = Defective wire and mill products output rate/annum

- b) Wire rod mill products output rate (WIRPOR) is defined as a rate variable and is given by the following equation:

$$\text{WIRPOR} = \text{WIREUP} * \text{WIRPRF} * \text{WRPRDF}$$

where WRPRDF = Wire rod products productivity factor, a constant

WIRPRF = Wire rod products production rate factor, a constant

- c) Defective wire rod mill products production rate (DWIRPR) is defined as a rate variable and is given by the following equation:

$$\text{DWIRPR} = \text{WIREUP} * (1 - \text{WIRPRF})$$

- ix) a) Wire rods inventory (WIRODI) is defined as a level variable and is given by the following equation.

$$\text{WIRODI} = \text{WIRODI} + \text{DT} * (\text{WIRPOR} - \text{WIRDSR})$$

where WIRPOR = Wire rods output rate/annum

WIRDSR = Wire rods sales rate/annum

- b) Wire rods sales rate (WIRDSR) is defined as a rate variable and is given by the following equation.

$$\text{WIRDSR} = \text{AWIRPO} * \text{WIRSRF}$$

where WIRSRF = Wire rods sales rate factor, a constant

54. Average input to sinter rate (ASINTR) is defined as a smoothed function as given below:

$$\text{ASINTR} = \text{SMOOTH} (\text{ISINTR}, \text{ASINTR}, \text{TASINT})$$

Where ISINTR = Input to sinter process rate

ASINTR = Smoothed value of ASINTR, initial

TASINT = Time delay in smoothing input to sinter processing rate

55. Average Iron ore addition to Blast Furnace rate (AIROBF) is defined as a smoothed function and is given below:

$$\text{AIROBF} = \text{SMOOTH} (\text{IROBFR}, \text{AIROBF}, \text{TAIROB})$$

Where IROBFR = Iron ore addition to BF rate

AIROBF = Smoothed value of IROBFR, initial

TAIROB = Time delay in smoothing Iron ore addition to BF rate

56. Average Sinter addition to BF (ASNTBF) is defined as a smoothed function and is given below:

$$\text{ASNTBF} = \text{SMOOTH}(\text{SNTBFR}, \text{ASNTBF}, \text{TASNTB})$$

Where SNTBFR = Sinter addition to BF rate

ASNTBF = Smoothed value of SNTBFR, initial

TASNTB = Time delay in smoothing Sinter addition to BF rate

57. Average Input to BF rate (AINPBF) is defined as a smoothed function and is given below:

$$\text{AINPBF} = \text{SMOOTH}(\text{INPBFR}, \text{AINPBF}, \text{TAINPB})$$

Where INPBFR = Input to BF rate

AINPBF = Smoothed value of INPBFR, initial

TAINPB = Time delay in smoothing Input to BF rate

58. Average Hot metal output rate (AHMTPR) is defined as a smoothed function and is given below:

$$\text{AHMTPR} = \text{SMOOTH}(\text{HMTOPR}, \text{AHMTPR}, \text{TAHMTP})$$

Where HMTOPR = Hot metal output rate

AHMTPR = Smoothed value of HMTOPR, initial

TAHMTP = Time delay in smoothing Hot metal output rate

59. Average slag production rate (ASLAGP) is defined as a smoothed function and is given below:

$$\text{ASLAGP} = \text{SMOOTH}(\text{SLAGPR}, \text{ASLAGP}, \text{TASLAG})$$

Where SLAGPR = Slag production rate

ASLAGP = Smoothed value of SLAGPR, initial

TASLAG = Time delay in smoothing slag production rate

60. Average Steel output rate (ASTELO) is defined as a smoothed function and is given below:

$$\text{ASTELO} = \text{SMOOTH}(\text{STELOR}, \text{ASTELO}, \text{TASTEL})$$

Where STELOR = Steel output rate

ASTELO = Smoothed value of STELOR, initial

TASTEL = Time delay in smoothing Steel output rate, a constant

61. Average Blooms output rate (ABLOMO) is defined as a smoothed function and is given below:

$$\text{ABLOMO} = \text{SMOOTH}(\text{BLOMOR}, \text{ABLOMO}, \text{TABLOM})$$

Where BLOMOR = Blooms output rate

ABLOMO = Smoothed value of BLOMOR, initial

TABLOM = Time delay in smoothing Blooms output rate, a constant

62. Average Billets output rate (ABILTO) is defined as a smoothed function and is given below:

$$\text{ABILTO} = \text{SMOOTH}(\text{BILTOR}, \text{ABILTO}, \text{TBILTO})$$

Where BILTOR = Billets output rate

ABILTO = Smoothed value of BILTOR, initial
TBILTO = Time delay in smoothing Billets output rate

63. Average MMSM products output rate (AMMSPO) is defined as a smoothed function and is given below:

AMMSPO = SMOOTH (MMSPOR, AMMSPO, TAMMSP)

Where MMSPOR = MMSM Products output rate

AMMSPO = Smoothed value of MMSPOR, initial

TAMMSP = Time delay in smoothing MMSM products output rate

64. Average Bar Mill Products production rate (ABMLPP) is defined as a smoothed variable and is given below:

ABMLPP = SMOOTH (BMLPPR, ABMLPP, TABMLP)

Where BMLPPR = Bar Mill products production rate

ABMLPP = Smoothed value of BMLPPR, initial

TABMLP = Time delay in smoothing Bar Mill Products production rate

65. Average Wire-Rod products output rate (AWIRPO) is defined as a smoothed variable and is given below:

AWIRPO = SMOOTH (WIRPOR, AWIRPO, TAWIRP)

Where WIR IRPOR, initial

TAWIRP = Time delay in smoothing Wire-rod Mill products output rate

4. Computer simulation of the Model:

The present model consists of a total of 158 equations having 52 level equations, 74 rate equations, 18 third order call delay functions and 14 smoothed level variables. All together 8 policies are tested and the results are verified with the available published data. The model is simulated using DYMO SIM Software package

The length of simulation for the model is taken as 20 years. Simulation is carried out with assumption that the problem description would remain valid for this period. Base year for the model was taken as 1994 and was run for a period of 20 years.

4.1 Calibration and Validation of the Model:

The model is calibrated and validated at every stage of its development. As suggested by Forrester (1968), Coyle (1977), Forrester and Senge (1980), Mohapatra et al (1994), validation has been treated as a continuous process.

The following five variables have been chosen for model validation:

- (i) Hot Metal production

- (ii) Liquid Steel Production
- (iii) Production of Prime Blooms
- (iv) Production of Bar Mill Products and
- (v) Production of Wire Rod Products

Data generated by the model over the period 1994-2003 is plotted against the actual production data of the plant for the same period for the aforesaid important parameters to consolidate the model further.

Fig 7 presents the production values for the hot metal from blast furnace along with the simulated values. There was a sudden drop in production of steel plant during 1999. This anomaly in production is due to the operational problems in Coke ovens and Blast furnace units of the steel plant. With these two major units not available fully, the production of plant was badly affected and this had a cascading effect on for down stream units. Towards the end of simulation period i.e., 2003, it can be seen that actual production and the predicted production are close to each other. In Fig 8 the production of liquid steel is represented. The behavior of the actual system is thus well represented by the model and the agreement is very good. Figs 9, 10 and 11 portray the production of blooms, bar mill products and wire rods. The figures exhibit similar trends as in Figs. 7 and 8 for hot metal and liquid steel. The Figs. 10 and 11 for bar mill and wire rods show that there is a steady increase in production from the year 2000 onwards.

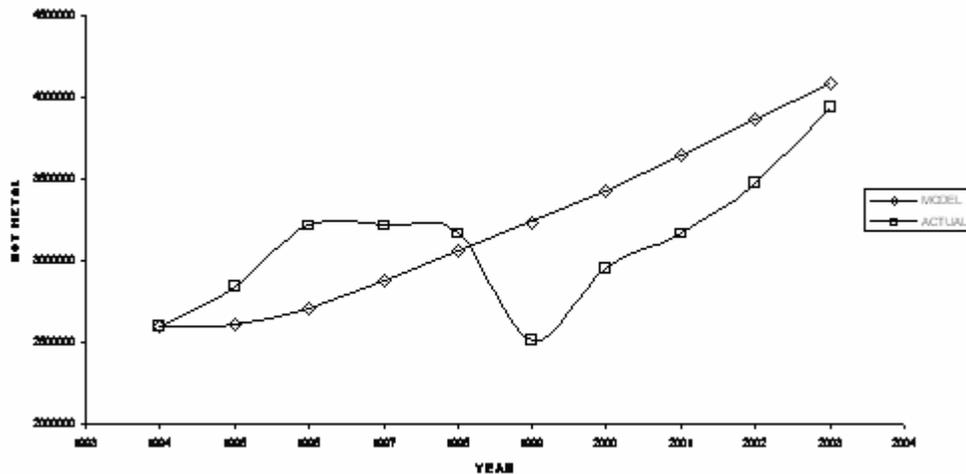


Fig.4 Hot Metal - Base Run

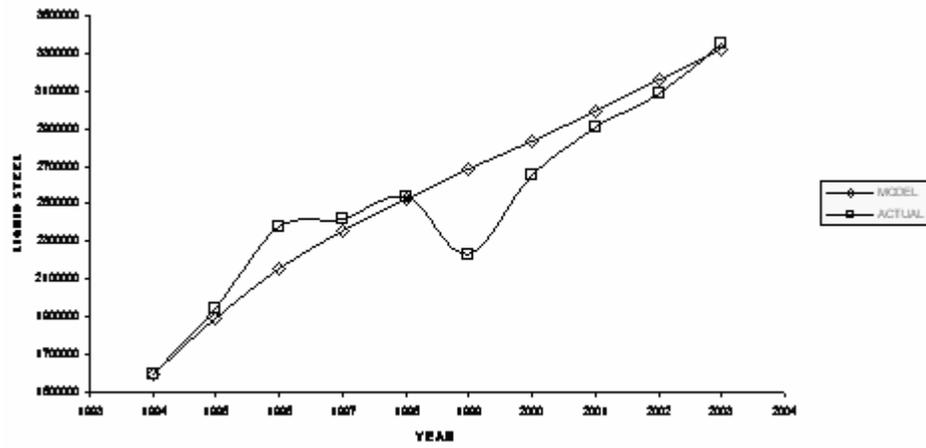


Fig.5 Liquid Steel - Base Run

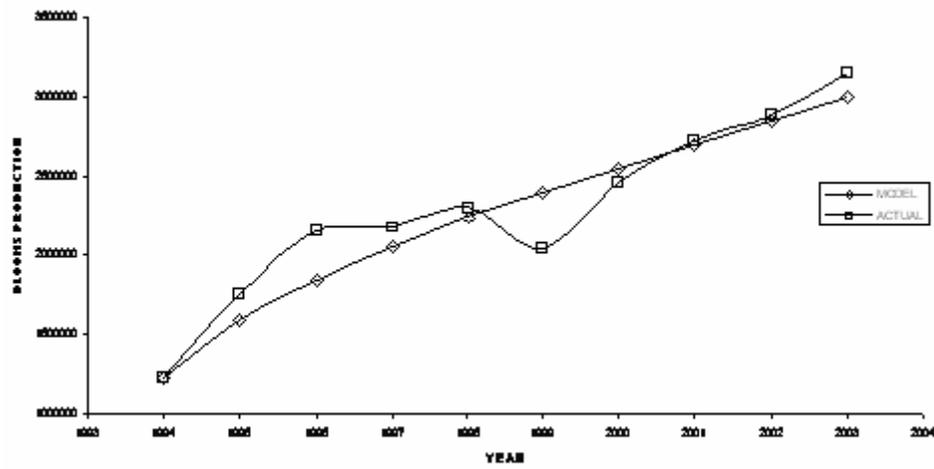


Fig.6 Blooms Production - Base Run

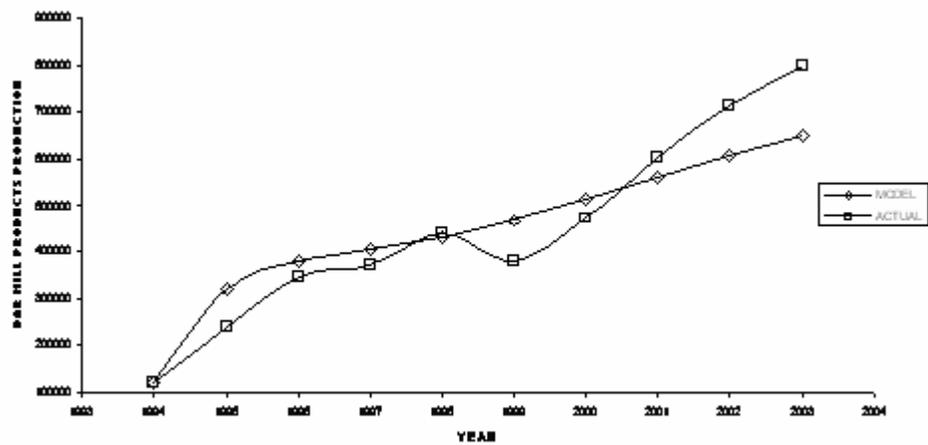


Fig. 7 Bar Mill Products - Base run

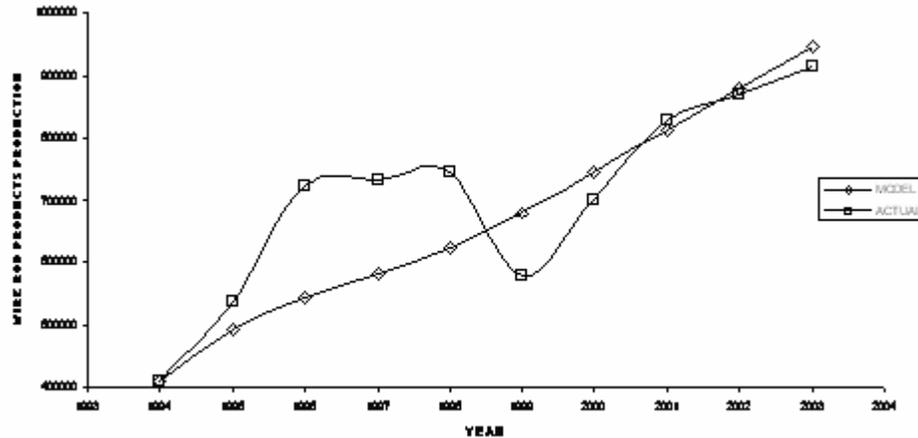


Fig.8 Wire Rod Products Base Run

4. 2. Tests of Model structure:

i) Structure verification test: The structure of the model was thoroughly validated such that it clearly resembles the structure of the real life system. The model consists of physical flows of raw material receipts, in- process materials, semi- finished and finished products. The important level variables considered in the model are production of coke, sinter, hot metal, liquid steel, prime blooms, billets and other finished products. Both the causal loop and flow diagrams consist of variables which can be easily identified in the real life system.

ii) Parameter verification test: All the parameters considered in the model correspond to real life system both conceptually and numerically. All these parameters can be identified in the real life system and they are consistent with the real life system.

iii) Dimensional consistency test: The model consists of 158 equations. All these equations are written and thoroughly checked for dimensional consistency between the influencing variables and resultant variables. Thus the model is found to be dimensionally consistent.

iv) Boundary adequacy (structure) test: As indicated by causal loop and flow diagrams, the factors considered in model have been adequate in addressing the various issues related to real life system. The model boundary set in this study, therefore, is considered adequate for the objectives with which the model is developed.

4. 3 Tests of Model behaviour

i) Behavioral reproduction test:

The simulated data along with the actual production data for the select parameters are presented in Table 1. It can be seen that they are in agreement. To enhance the confidence in the model further, t- test and F- test are conducted. The results of the tests are presented in the Table 2 and test statistic is well within the 95% confidence limits. Therefore, it can be said that the model represents the dynamic behavior of the system very well and it can be extended to generate future scenarios which form the basis for formulating policies for the growth of the company.

Table 1: Comparison of Model generated and Actual values for select variables

YEAR	Hot Metal		Liquid Steel		Blooms		Bar Mill Products		Wire Rod Products	
	Actual	Model	Actual	Model	Actual	Model	Actual	Model	Actual	Model
1993-94	2.600	2.600	1.600	1.600	1.220	1.220	0.120	0.120	0.410	0.410
1994-95	2.836	2.607	1.940	1.888	1.755	1.582	0.238	0.320	0.537	0.503
1995-96	3.213	2.710	2.381	2.158	2.155	1.838	0.344	0.382	0.725	0.553
1996-97	3.213	2.875	2.423	2.360	2.179	2.055	0.370	0.405	0.734	0.584
1997-98	3.165	3.051	2.541	2.526	2.306	2.236	0.440	0.428	0.744	0.619
1998-99	2.510	3.238	2.225	2.682	2.041	2.396	0.381	0.461	0.579	0.669
1999-00	2.942	3.435	2.656	2.837	2.468	2.546	0.474	0.502	0.700	0.729
2000-01	3.165	3.640	2.909	2.994	2.724	2.695	0.604	0.546	0.827	0.794
2001-02	3.485	3.866	3.082	3.156	2.691	2.845	0.715	0.590	0.868	0.858
2002-03	3.941	4.093	3.356	3.325	3.155	3.000	0.799	0.633	0.915	0.921

Table 2: t- test and F-test for Model and Actual values for selected variables

Variable	Actual		Model		t- test at 95% confidence level= 2.11	F- test at 95% confidence level = 3.18
	Mean	Standard Deviation	Mean	Standard Deviation		
Hot Metal	3.107	0.419	3.212	0.534	0.4884	1.625
Liquid Steel	2.511	0.525	2.55	0.557	0.1704	1.125
Blooms	2.289	0.563	2.241	0.571	-0.188	1.03
Bar Mill Products	0.448	0.208	0.439	0.148	-0.11647	1.99
Wire- Rod Products	0.704	0.156	0.664	0.161	-0.556	1.07

ii) **Behaviour prediction test:** Valid prediction of the real system behaviour can be made only if the model structure, the managerial policies and time variation of

exogeneous variables could be predicted (Mohapatra 1994). The model is run for the period from 2004 to 2013 and observed that the results of the model are identical with that of the values predicted by the management. This is vindicated by the results for period 2004 to 2006.

- iii) Behaviour anomaly test:** The model did not produce any behaviour anomalous to that of the real system.
- iv) Family member test:** The model has been developed for an integrated steel plant located in Visakhapatnam. But it is generic in nature and with appropriate modifications in the initial values of the level variables and parameters; it can be applied to any other steel plant either in India or elsewhere globally.
- v) Surprise behaviour test:** The model did not produce any surprise or counter intuitive behaviour.
- vi) Boundary adequacy (behaviour) test:** This test was intended to check whether the model boundary can be expanded to include other related aspects like domestic sales, export sales, owning captive mines. However, at aggregate level inclusion of these factors is not expected to produce significance changes in the model results.
- vii) Behaviour sensitivity test:** The model was tested for changed values of various parameters. Qualitatively the model retains its behaviour for all the variables.

4.4 Policy options:

Having established that the SD model represents the production activities of the plant under study with confidence, the model is now extended to formulate and develop policies to improve the performance of the company. SD model is used to design a set of policies that are aimed at capacity expansion and determining optimal product mix.

These policies can be divided in to pure and mixed policies and can be categorized in to three as below:

- i) Increasing productivity of various production facilities
- ii) Optimising product mix and
- iii) Increasing the productivity and optimising product mix as well

The demand for steel and its products is increasing continuously owing to the emphasis given by the new economic policy to the development of infrastructure for which steel is a vital input. The plant under study should be able to meet the enhanced demand for steel by its customers.

The various policies proposed in the study are listed below.

Policy 1: Base Run:

In this policy, it is assumed that the present trend with reference to capacities and that of demand persists in future also and there will not be any significant changes.

Policy 2:

20% increase in the productivity of Hot Metal and Liquid Steel: other conditions as in the base run.

This policy tests what happens if the productivity of Hot Metal and Liquid steel is increased by 20% above the present level.

Policy 3:

25% increase in the productivity of Hot Metal and Liquid Steel: other conditions as in the base run:

This policy tests what happens if the productivity of Hot Metal and Liquid steel is increased by 25% above the present level.

Policy 4:

20% increase in the allocation blooms to Billets: other parameters as in the base run:

At present Blooms are utilized for producing Billets and MMSM products. Billets are inturn used for producing down stream products. As there is a conceived demand for Wire Rod products and Bar Mill products over MMSM products, this policy is designed to check implications on the system if more blooms are diverted to produce Billets.

Policy 5:

25% increase in the productivity of Hot Metal and Liquid Steel: Change in the product mix (20% increase in the allocation of billets to Wire Rod Mill products): other conditions as in the base run:

This is a mixed and designed to check the implications of changes in product mix when the productivity is increased. As already mentioned, there is a perceived demand for Wire rod products. In view of the same, allocation of Billets to Wire Rods production is increased by 20% and there is a proportionate reduction in the allocation of Billets for production of Bar Mill Products. The sale of Billets remains unchanged.

Policy 6:

25% increase in the productivity of Hot Metal and Liquid Steel: Change in the product mix by allocating 40% of billets to Bar Mill products and 60% to Wire Rod Mill products with no Billet sales: other conditions as in the base run:

This is also a mixed policy and designed to explain the impact of change in product mix at higher productivity levels. As per this policy, allocation of Billets is made in the proportion of 40:60 to Bar Mill products and Wire Rod products. There is no sale of Billets.

Policy 7:

25% increase in the productivity of Hot Metal and Liquid Steel: 10% increase in productivity of Billets; Change in the product mix by 20% decrease in the allocation of Billets to Bar Mill products and 20% increase to Wire Rod Mill products with Billet sales unchanged): other conditions are as in the base run:

This policy is a mixed policy and is designed to explain the impact of increase in productivity of Billets by 10% and at the same time changing the product mix. The allocation of Billets to Bar Mills is reduced by 20% and at the same time changing allocation of billets to WRM is increased by 20%. There is no change in the sale of Billets.

Policy 8:

25% increase in the productivity of Hot Metal and Liquid Steel: 10% increase in productivity of Billets; Change in the product mix (30% of billets are allocated to Bar Mill products and 70% to Wire Rod Mill products; Billet sales is not allowed): other conditions are as in the base run:

This policy is mixed policy and is designed to explain the impact of increase in productivity of Billets by 10% and at the same time change in the product mix. In this policy, the implications of the change in product mix are studied. The allocation of Billets to Bar Mill and Wire Rod Mill products is made in the proportion of 30:70 with no billets available for sale.

4.5 Results of model simulation

After simulating the model for different policy options listed above, the behaviour of key variables was examined in detail. The base run(Policy- 1) results have also been compared with the available data. A comparative study of various policy results has been made.

The results of the base run for the selected variables are presented in Table .4.

Table. 3: Base run results of key variables

(Million Tonnes)

Sl. No.	Variables	1994	1997	2000	2003	2006	2009	2013
1	Hot Metal	2.6	2.87	3.33	3.65	3.86	3.972	4.01
2	Liquid Steel	1.6	2.54	3.10	3.462	3.72	3.89	3.98
3	Prime Blooms	1.22	2.15	2.78	3.18	3.45	3.64	3.76
4	Wire Rod Mill Products	0.12	0.41	0.52	0.68	0.81	0.89	0.96
5	Bar Mill Products	0.41	0.58	0.76	0.99	1.17	1.30	1.40

4.6 Policy analysis:

The results generated by the model under different policy options have been depicted in Figs. 12 to 18. A comparison of the performance under different policy options is given in Table 4.

The first two policies intend to increase the hot metal and liquid steel production and correspondingly the output of the semi finished and finished products in the same

proportions as in the base run. The results are presented in graphical form in Figs.12 and 13 respectively.

According to policy-1, the hot metal production attains a steady level of about 4.8 Mt by the year 2007. Similarly policy-2 leads to a steady production of 4.9 Mt by the year 2007 as seen from Fig. 4.9. The overall trend in both the cases is similar to that of base run, however with higher levels of production; this level of production can be achieved with the existing blast furnaces. Study of blast furnaces similar to those at this plant shows that the hot metal production can be enhanced beyond 4.2 Mt to 5 Mt by natural gas injection, pulverised coal injection and oxygen enrichment. Already some of these measures are being implemented by the management. The liquid steel production of 3.60 Mt was achieved in the year 2005-06 with a capacity utilization of 120%.

It has been assessed that the liquid steel production of 3.6 Mt per annum is possible from the existing steel melt shop. Production of liquid steel cannot go beyond this with existing converters. Therefore, to attain the steel production of 5Mt, it would be necessary to add new facilities to SMS and also facilities in the downstream. The model shown in Fig. 13 predicts only gradual increase in production. It is evident from the fig. 13 that the liquid steel production of 4.7 Mt and 4.8 Mt is predicted by the policy 1 and policy 2 respectively. This is much higher than the present level of about 3.6 Mt. The substantial rise in liquid steel production will be possible only with expansion of the steel melting shop of the plant.

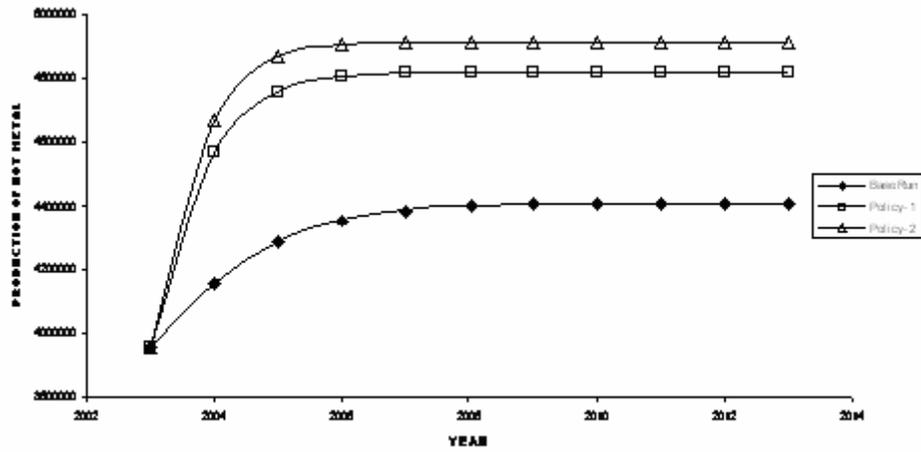


Fig. 9 Production of Hot Metal with Policy Changes

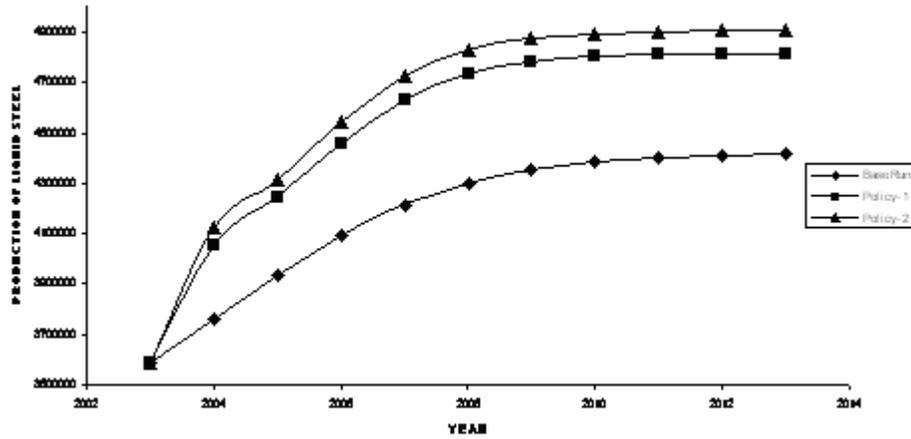


Fig. 10 Production of Liquid Steel with Policy Changes

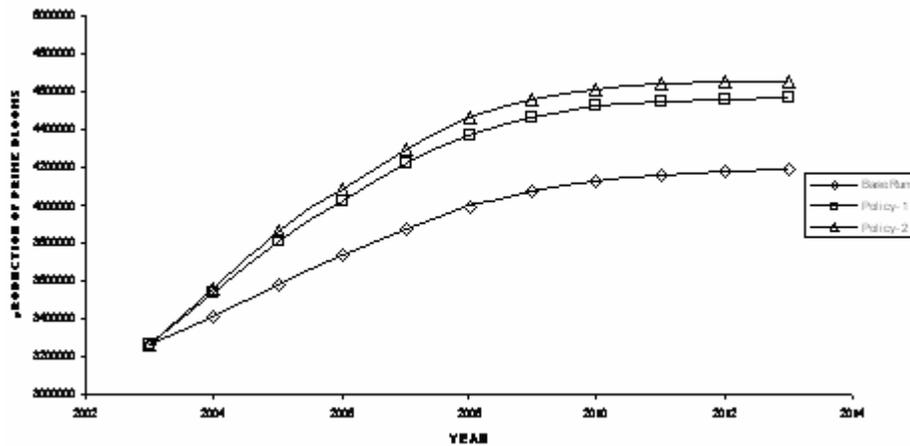


Fig. 11 Production of Prime Blooms with Policy Changes

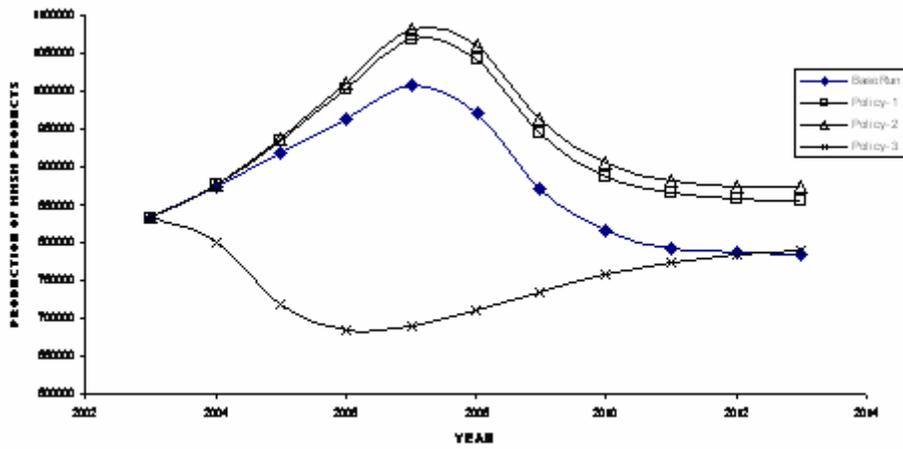


Fig. 12 Production of MMSM Products with Policy Changes

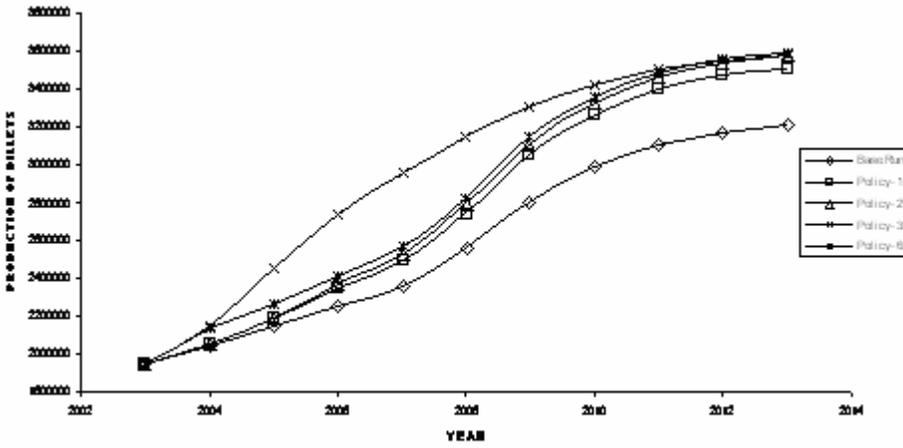


Fig. 13 Production of Billets with Policy Changes

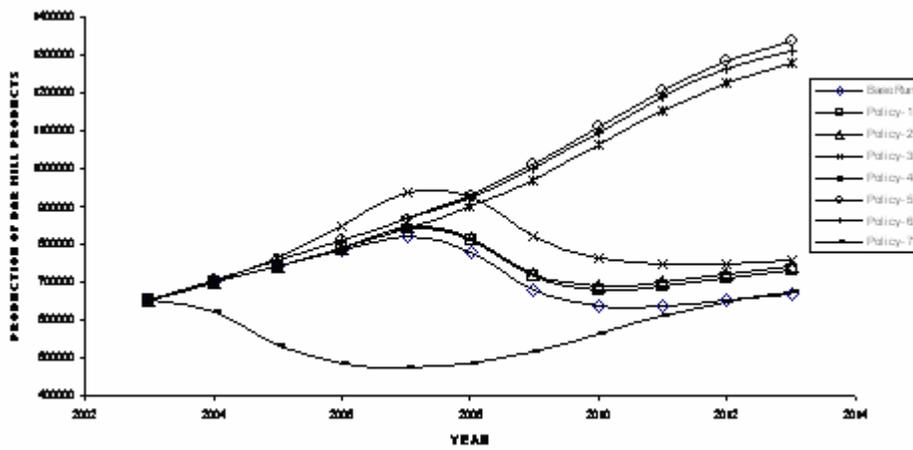


Fig. 14 Production of Bar Mill Products with Policy Changes

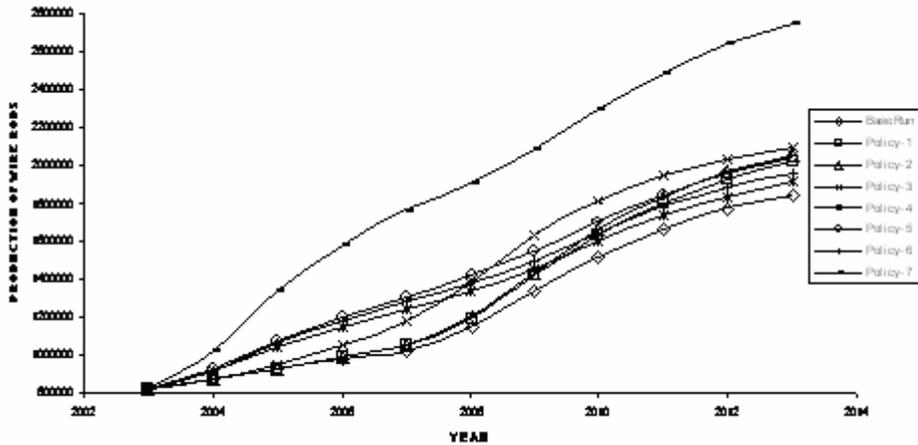


Fig. 15 Production of Wire Rod Products with Policy Changes

Liquid steel is first converted into semi-finished products viz., blooms and billets in continuous casting. The additional liquid steel when converted into blooms will give rise to production rates of about 4.4 Mt according to policy- 1 and 4.5 Mt as per the policy- 2 as shown in Fig. 14. This entails augmentation of bloom/ billet casters capacity. The policy 4 is concerned with production of semi-finished products where as the remaining policies consider many combinations of finished products so as to optimize product mix. In Fig.15, the production of billets can be seen to increase gradually before reaching a plateau. Compared to the base run, the policies- 5 to 8, all yield a value of about 2.8 Mt by the year 2008 whereas the policy- 1 predicts a value of about 3.2 Mt. With the percentage growth assumed under different policies, a maximum rate of billets of 3.3 to 3.4 Mt/ annum is predicted for the year 2013. However, the policy 10, predicts a value of about 3.2 Mt by the year 2008 and 3.3 Mt by the year 2009. Such a high increase of billets will be possible only if new continuous casting machine is installed to convert liquid steel into semi-finished products and then into finished goods.

In view of the above, it is recommended to install a billet caster of 1.6 Mt facilitating the increased production. Fig 15 shows the variation of MMSM products over the period 2004-2013. It can be seen that the production of these products increases and reaches a maximum of about 0.95 to 1.1 Mt in the period 2006–2008 and comes down to stabilize at a level of about 85,000 tonnes. This is more or less true for all the policies indicated including the base run except policy-3, which shows a reverse trend. As per this policy,

the proportion of merchant mill production is drastically reduced to about 18.5% of the finished products. This will result in decrease in production of MMSM products. As per the policies- 1 and 2, increasing the steel production and keeping the proportion of MMSM products same as in the base run, the proportion of MMSM is bound to increase similar to base run as shown in Fig. 12. In the prevailing situation representing the base run, the emphasis should be given to production of remunerative products like wire rod and bar mill products. Thus, there will be a gradual shift in to these products at the cost of Merchant mill products. However, the existing Merchant mill cannot be shutdown and the plant has to continue with production of MMSM and operate it at its optimum level of around 80,000 tonnes.

Table 4: Comparison of policy results of key variables
(Million Tonnes)

Sl. No.	Variables	Year	P ₁	P ₂	P ₃	P ₄	P ₅	P ₆	P ₇	P ₈
1	Hot Metal	2004	3.73	4.10	4.19	4.10	4.19	4.19	4.19	4.19
		2007	3.91	4.58	4.74	4.58	4.74	4.74	4.74	4.74
		2010	3.99	4.83	4.94	4.83	4.93	4.94	4.94	4.94
		2013	4.01	4.86	4.95	4.86	4.95	4.95	4.95	4.96
2	Liquid Steel	2004	3.56	3.84	3.90	3.84	3.90	3.90	3.90	3.90
		2007	3.78	4.21	4.31	4.21	4.39	4.31	4.31	4.31
		2010	3.91	4.57	4.70	4.57	4.70	4.70	4.71	4.71
		2013	3.98	4.73	4.84	4.73	4.83	4.84	4.84	4.84
3	Prime Blooms	2004	3.28	3.40	3.42	3.39	3.42	3.42	3.42	3.42
		2007	3.53	3.86	3.94	3.86	3.94	3.94	3.94	3.94
		2010	3.68	4.24	4.36	4.23	4.36	4.36	4.36	4.36
		2013	3.76	4.46	4.56	4.46	4.56	4.56	4.56	4.56
4	Bar Mill Products	2004	0.79	0.73	0.73	0.73	0.69	0.73	0.70	0.69
		2007	0.84	0.86	0.86	0.96	0.70	0.86	0.72	0.68
		2010	0.92	0.99	1.00	1.17	0.80	1.00	0.81	0.76
		2013	0.96	1.09	1.12	1.31	0.89	1.12	0.90	0.84
5	Wire Rod Mill Products	2004	1.06	1.05	1.06	1.06	1.08	1.07	1.09	1.12
		2007	1.22	1.25	1.26	1.40	1.39	1.32	1.42	1.56
		2010	1.33	1.44	1.46	1.71	1.62	1.54	1.64	1.81
		2013	1.40	1.59	1.63S	1.90	1.82	1.71	1.83	2.01

Fig 17 portrays the production of bar mill products. The policies- 1,2 and 3 show an initial increase up to a maximum of 80,000 - 1,00,000 tonnes followed by a leveling off to 65,000 - 75,000 tonnes. According to policies 4, 5 and 6, the production continuously increases and reaches the highest level of approximately 1.3 Mt. and this high production levels will only be possible with additional capacity in bar mill products. However, these products are less remunerative compared to wire rods and hence it would be prudent to operate the existing mill at its full capacity of about 0.9 Mt only. As per the policy 7, in which case the wire rods would be given preference over the other finished products, the bar mill production will be on the lower side i.e., around 0.65 Mt. This production is lower than the installed capacity of the bar mill. It is advisable to run the mill to its maximum capacity of about 0.8 Mt. Fig 18 shows the variation of wire rod production for the period 2004-2013. It can be seen that wire rod production shows a continuous increase over the entire period. Other than policy- 7, all policies lead to a steady rise up to 1.7 - 1.9 Mt by the year 2013. As per the policy- 7, there is rapid increase in production by the year 2008 to a level of 2.0 Mt by the year 2009. Whether it is policy- 7 or the others, doubling of production should take place. As the wire rods are highly priced and are much in demand, the plant has to go in for expansion of the wire rod mill to meet the customer requirements. This result is in agreement with the corporate plan envisaged for the plant. However, the policy-7 shows a continuous growth reaching a level of 2.8 Mt by the year 2013. Given the high levels of efficiency, with a wire rod mill of 2 Mt installed capacity, it would be possible to achieve 2.4 Mt at an efficiency of 120%. Production beyond this level would not be realistic even though the model predicts such figures.

5. Conclusions:

Based on the detailed discussion on the results, the following conclusions are drawn.

1. System dynamics (SD) model portrays the behavior of the operations of the integrated steel plant under study very effectively more or less over the entire period from 1994-2003 as established by the graphical representations and the statistical tests. There is a discrepancy in the production during the time period 1998-99.

2. The anomalous behavior shown by the actual plant data compared to the model generated data in this time period can be attributed to extraneous factors such as damage to the coke ovens and capital repairs of blast furnace which are beyond the scope of modeling.
3. SD model has been extended for a period of another 10 years from 2004 to 2013 to design policies for possible implementation by the steel plant. Of all the policies tested, policy- 7 resulted in maximization of wire rod production is the most desirable one.
4. The product mix suggested as per the model consists of 2.0 Mt of wire rods, 0.75 Mt of MMSM products, 4.7 Mt of prime blooms and 3.2 Mt of billets by the year 2008. Also, a hot metal production of 4.9 Mt and liquid steel production of 4.9 Mt is predicted by the model.
5. The Production levels targeted and envisaged in the Phase-I expansion of the Visakhapatnam Steel Plant is % Mt of Hot metal and liquid steel respectively. The finished products are expected to attain a level of 0.9 Mt of MMSM 0.75 Mt of, WR products of 2 Mt, seamless pipe of 0.15 Mt. The figures predicted by the best of the policies designed by SD model given above are thus in very good agreement.

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