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NATIONAL CENTER FOR ANALYSIS OF ENERGY SYSTEMS
DEPARTMENT OF ENERGY AND ENVIRONMENT

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F.T. SPARROW,* D. PILATI, T. DOUGHERTY,** E. MCBREEN, L.L. JUANG

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*Purdue University, W. Lafayette, IN.
**General Motors Institute, Warren, MI.

ECONOMIC ANALYSIS DIVISION

NATIONAL CENTER FOR ANALYSIS OF ENERGY SYSTEMS
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SUMMARY

The iron and steel industry process model depicts expected energy consumption characteristics of the iron and steel industry and ancillary industries for the next 25 years by means of a process model of the major steps in steelmaking, from ore mining and scrap recycling to the final finishing of carbon, alloy, and stainless steel into steel products such as structural steel, slabs, plates, tubes, and bars. Two plant types are modeled: fully integrated mills and mini-mills.

User-determined inputs into the model are as follows:

a. Projected energy and materials prices.
b. Projected costs of capacity expansion and replacement.
c. Energy conserving options, both operating modes and investments.
d. The internal rate of return required on investment.
e. Projected demand for finished steel.

Nominal input choices in the model for the inputs listed above are as follows:

a. National Academy of Science Committee on Nuclear and Alternative Energy Systems Demand Panel nominal energy price projections for oil, gas, distillates, residuals, and electricity and 1975 actual prices for materials.
b. Actual 1975 costs.
c. See Table 1; new technologies can be added.
d. 15% after taxes.
e. 1975 actual demand with 1.5%/yr growth.

The model reproduces the base-year (1975) actual performance of the industry; then given the above nominal input choices, it projects modes of operation and capacity expansion that minimize the cost of meeting the given final demands for each of 5 years, each year being the midpoint of a 5-year interval. The output of the model includes the following:

a. Total energy use and intensity (Btu/ton) by type, by process, and by time period.
b. Energy conservation options chosen.
c. Utilization rates for existing capacity.
d. Capital investment decisions for capacity expansion.

Table 1

Energy Conservation Options

I. Raw Material Purchasing, Mining, and Mine-Mouth Processing
   - a. Increased dependence on imported pellets and concentrates
   - b. Increased use of recycle, prompt, and obsolete scrap

II. Raw Material Processing at the Plant
   - *a. Dry coking substituted for conventional wet quenching**

III. Iron Production
   - a. Substitution of coke for hydrocarbons as a Btu source
   - b. Substitution of powdered coal for coke as a Btu source
   - c. Operation of blast furnaces at higher temperature to improve combustion efficiency (requires relining and rebricking)
   - *d. Installation of bell-less tops
   - *e. Construction of new blast furnaces capable of higher top pressures
   - f. Increased burden quality by shift to high pellet charges
   - *g. Construction of Jordan blast furnace - a coal gasifier with by-product iron**

IV. Steel Production
   - *a. Higher scrap charges for BOFs by installation of scrap preheaters**
   - *b. Increased use of off-gases from other processes as a Btu source
   - *c. Substitution of BOF furnaces for the less efficient open-hearth furnaces
   - *d. Conversion of open-hearth furnaces to Q-BOP
   - *e. Increased use of oxygen injection
   - *f. Installation of hoods to collect steelmaking off-gases on BOFs, Q-BOPs, and electric-arc furnaces

V. Casting and Forming
   - *a. Use of continuous casting of slabs** and billets

VI. Finishing Mills
   - a. Monobeam reheat furnaces** substituted for pusher type

VII. Energy Conversion Processes
   - a. Increased use of low quality off-gases by blending with fossil fuels
   - *b. Cogeneration of steam and electricity
   - *c. Use of coal off-gas boilers
   - *d. Use of gas turbines for cogeneration

*Qualifies for investment tax credit.
**Requires expenditures for R & D before use.

I. INTRODUCTION

A. Overview of the Model

The model is a dynamic activity analysis model of two types of mills in the domestic iron and steel industry*, integrated and mini-mills. The activities of such mills are indicated in Figures 1 and 2. In order to incorporate most of the energy used by the industry, indirect as well as direct, the industry model includes extraction and transportation of the major raw materials: iron ore mining, concentrating, and transportation; coal mining and transportation; and scrap "mining" and transportation. The two types of mills represented in the model are (a) fully integrated plants which have the capacity to beneficiate iron ore, produce coke, convert iron ore to iron in blast furnaces, convert iron to steel by any of four types of steel furnaces, semi-finish, and finally finish steel; and (b) "mini-mills" which convert scrap to steel in electric-arc steel furnaces.

Three types of steel are produced: carbon, alloy, and stainless. Carbon steel is fabricated into three classes of products: (a) heavy structural steel, rails, and other bloom-based products; (b) plates, forms, and other slab products; and (c) tubes, bars, and other billet products. Mini-mills produce a more limited range of products, confined to structural bars and light forms, and compete with the integrated mills for this particular demand. It is assumed that specialty steels are made only in billets and are made only in electric-arc furnaces for quality control reasons, even though minor amounts of these steels are known to be made in other furnaces and in other forms.

Capital stocks are vintaged according to their ability to be retrofitted with more modern ancillary energy conservation equipment. They are characterized by size and age, which are reflected in higher operating and maintenance costs for older, smaller-scale equipment. The number of vintages and the number of operating technology options are listed below each process in Figures 1 and 2.

*This is hardly a novel idea: the first model described in the operations research literature was Tibor Fabian's effort[1] 20 years ago!

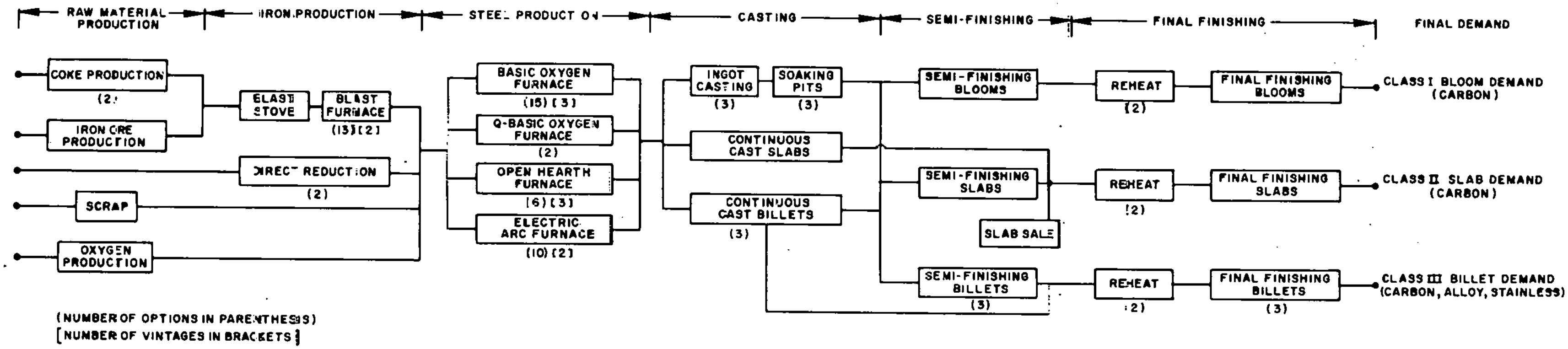

Figure 1. Flow chart of integrated steel industry

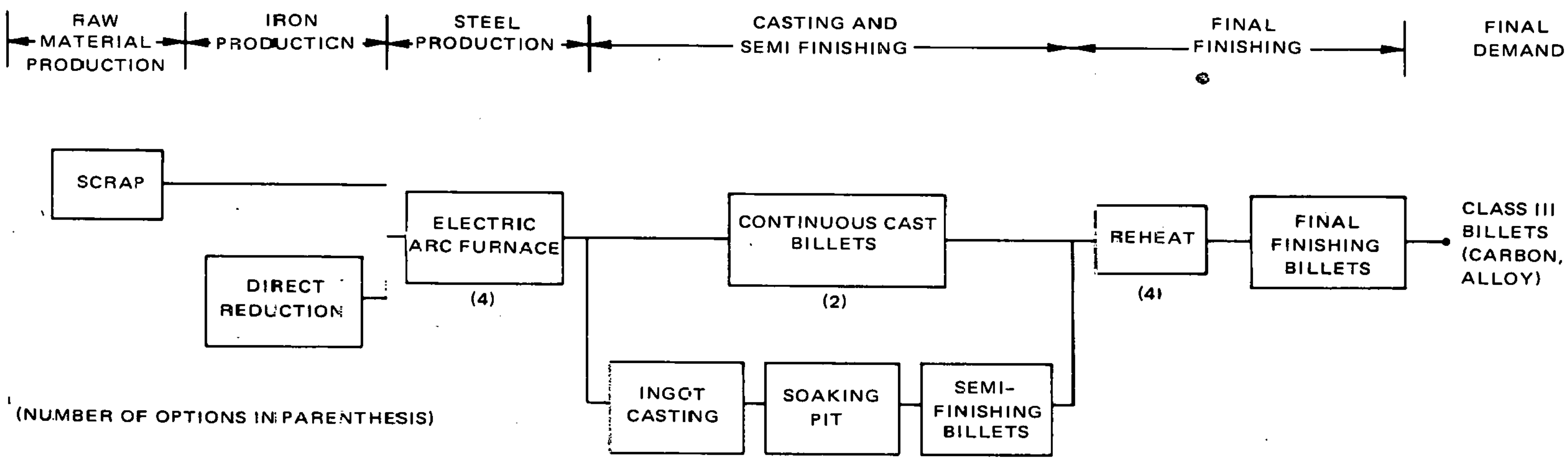

Figure 2. Flowchart of mini-mill steel industry

The demand for domestic steel and the supply of both scrap and domestic iron ore are price sensitive in the model, in that domestic steel competes for domestic demand with imports, while domestic ore competes with ore imports for the domestic ore demand. The exhaustible nature of domestic ore is reflected by constraints on the availability over the 25-year horizon of three "ore bodies" each with their own extraction costs. The price sensitivity of the scrap supply is based on a recent econometric study.[2]

The model is a "technocratic" model of the iron and steel industry in that the industry is assumed to act collectively so as to minimize the cost of fulfilling a given set of demands. Thus, it acts as if it were a cartel or monopoly, assigning units of output to the least-cost available production method, without regard for who owns the capacity being utilized. To the extent that the existing steel industry departs from this mode of operation, the model departs from a positive description of industry behavior and becomes instead a normative model. Certainly there is some departure from cost-minimizing behavior in the industry; otherwise, more of the smaller, less efficient capacity of the marginal producers would have been replaced by the large, more modern units of the best-practice plants and firms instead of lingering around the industry as it is observed to do. Nonetheless, market forces do work, even in an industry dominated by large firms, and such marginal plants cannot last forever by selling "below cost" to meet the competition; sooner or later they will be closed down and replaced with more modern equipment.

The model has five periods, each representing the middle year of a 5-year interval. The planning horizon is 25 years. The initial capacities and demands are those for the industry during 1974-75.

The optimization problem is given the following: (1) the sequence of demands that must be met by domestic production or imports; (2) initial capacities, vintages, and characteristics of the capital stock; (3) current and projected prices for all inputs including energy; (4) the available modes of operation for each of the activities; (5) an estimate of capital availability in the form of retained earnings and new stock issues to finance expansion and replacement of equipment (assumed to be a function of the final demand growth rates in the model and the historical relation between demand and capital availability). Its solution gives the time sequence of production and capacity expansion and the capacity retrofit decisions which minimize the present value of the cost of capital for the iron and steel industry, taken as 15% after taxes.

Figure 3 shows the energy flows for the entire industry in 1973, expressed in 10^6 Btu per ton of finished steel produced.[3,4] Table 1 (in the summary above) gives the operating options, retrofit opportunities, and capacity additions which can potentially contribute to total enegy conservation in the industry or reduce the industry's dependence on hydrocarbons as a source of energy, and also indicates which need R&D dollars prior to introduction. (Some obvious options are not now in the model: form coke, electric induction heating, external desulfurization, etc.; they await later versions of the model. A 1976 AISI report[5] contains an exhaustive list of the popular options.)

B. Description of the Methodology

The heart of the problem is to model the cost-minimizing behavior of the iron and steel industry in such a way that all the substitutabilities and complementarities in the production chain are explicitly spelled out. The methodology used is activity analysis. (For other examples, see Manne and Markowitz.[6])

The basic building blocks of activity analysis are as follows:

a. A set of activities (1,2,...,k,...) which produce outputs in the amount $X^1, X^2, \ldots, X^k, \ldots$.

b. For each activity k, a set of technologies (1k,2k...,jk,...) which produce output of type k in the amount $X_1^k, X_2^k, \ldots, X_j^k, \ldots$. (Note that $\sum_j X_j^k = X^k$.)

c. A set of resources (1,2,...,i,...) used by the technologies, and a set of prices $(P_1, P_2, \ldots, P_i, \ldots)$ which give the cost per unit of each resource.

d. A set of technology coefficients a_{ij}^k which give for each technology j producing output k the unit input requirements for resource i per unit output. ($a_{ij}^k < 0$ denotes an output).

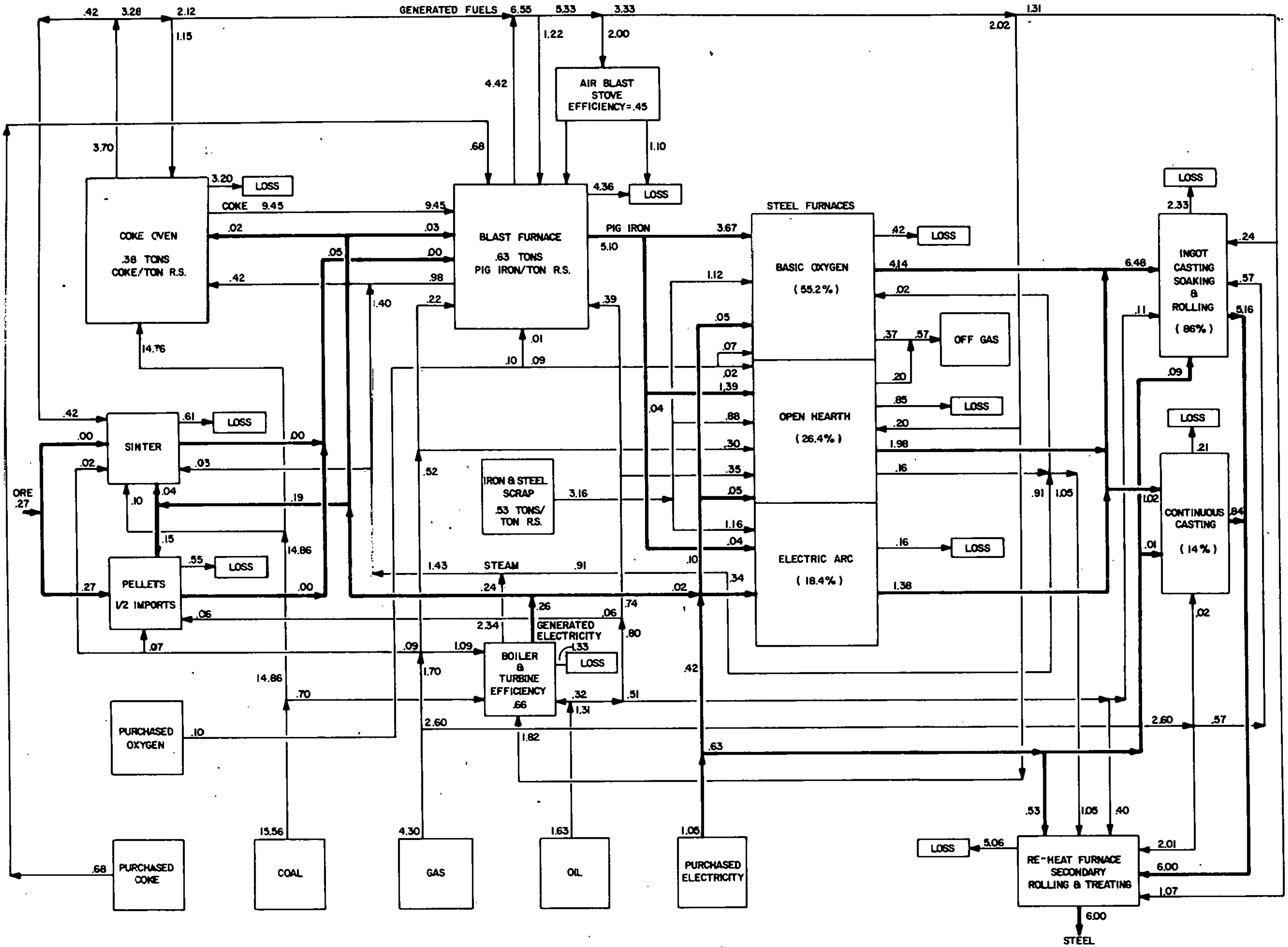

Figure 3. Energy flow for the U.S. steel industry (10^6 Btu/ton raw steel)

e. A set of final products $(1,2,\ldots,F,\ldots)$ and a set of time-dependent demands $R_F^1, R_F^2, \ldots, R_F^t, \ldots$ for each final product F, which may be price sensitive.

Resources can be categorized into four types: (a) purchased inputs, indexed in the set I (labor, material), acquired from outside the firm or organization at some given price or price schedule; (b) energy inputs to the production process; (c) intermediate products, indexed in the set $\tilde{K}$ as products of some activity within the firm or organization, and in the set $\tilde{M}$ when used as resources for subsequent activities; and (d) durable resources or equipment whose capacity is utilized by the activity, indexed in the set $M - M_1$ for existing technologies, and in the set M_1 for new technologies which require R&D expenditures prior to utilization; additions to the stock of durable resources add to the capacity of all future time periods up to the retiring of the equipment. The availability of the resource in all cases represents the stock of that resource on hand at the beginning of the period in question. It can be augmented during the period for the case of purchased inputs and intermediate products, but only with a lag in the case of durable resources because of the delay between the decision to invest in new capacity and the time when the new capacity comes into use.

Four types of activities indexed on k are distinguished in the models: purchase of nondurable resources, denoted by PI_k, $k \in I$; purchase of durable resources, DR_k, that either require ($k \in M_1$) or do not require ($k \in M - M_1$) R&D expenditures prior to purchase; production activities that transform resources into intermediate outputs, denoted by X_j^k, with k in the set $\tilde{K}$; and activities that transform resources into final outputs, again denoted by X_j^k, but with k in the set K.

Constraints indexed on i are of five types: (a) accounting constraints ($i \in I$) which ensure that the total utilization of a purchased input equals the total purchase of that input; (b) capacity constraints ($i \in M$) which require that the level of an activity not exceed its capacity; (c) materials balance constraints ($i \in \tilde{M}$) which ensure that the input requirements for intermediate products equal their production from prior activities; (d) demand constraints ($i \in K$) which ensure that activities which produce final goods produce an amount sufficient to meet final demands; and (e) variable constraints which ensure non-negative or integer values for the variables in the problem.

Since each technology has associated with it a set of resource requirements expressed in terms of units of capacity utilized and units of purchased inputs and intermediate products consumed, each has a cost. The optimization problem associated with the activity analysis is to choose that set of activities and set of technologies for the activities which satisfies the demand specified for the final products at minimum cost.

Choice enters the model via several routes. First, there may be several different combinations of activities which can produce the given product, each representing a different sequence or combination of activities. Second, even if there is a unique combination of activities which produces the product, there may be many possible technologies that can be chosen to accomplish each activity.

The objective function is the industry's after-tax cost of meeting the demands; hence it must include both the marginal tax rate and the allowed depreciation schedule.

The after-tax cash expenditure flow in any period t is of the form

$$\text{(a)} \quad (1 - \tau)EX^t - \tau D^t + \alpha^t DR^t$$

where

τ = the profits tax rate,
EX^t = total operating expenses in t,
D^t = allowed depreciation in t,
DR^t = durable resource investment in t, and
α = capital cost per unit of DR^t.

To see this, suppose revenues in t are R^t. Then after-tax cash-flow profits (assumed to be positive) are revenues, less operating expenses, less profits taxes, less durable goods expenditures:

$$\text{(b)} \quad R^t - EX^t - \tau(R^t - EX^t - D^t) - \alpha^t DR^t \; .$$

If demands are constant and must be met at fixed prices, R^t is constant, and maximizing (b) is equivalent to minimizing (a).

In any given period t, then, the objective function for the firms would be to minimize (a). The first term represents the after-tax operating expenses for all technologies in t; the second, allowed depreciation on all capital expenditures prior to t expressed as the reduction in tax liability; and the third, expenditures on capital equipment in t for all technologies. In the dynamic formulation, the private sector would discount future expenses by the cost of capital r, and the firm would minimize the present value of (a) over a given planning horizon.

Equation (c) summarizes the notions introduced previously; the energy terms are broken out of both the objective function and the constraint set. Constraints (.1) and (.1a) are the accounting equations which ensure that use of non-energy (.1) and energy (.1a) inputs equals the amounts purchased. Constraint (.2) ensures that utilization of the capacity of a given technology does not exceed the capacity available. Constraint (.3) represents the set of materials balance equations for all intermediate products. Constraint (.4) ensures that production of final products is at least as large as final demand. Constraint (.5) ensures that all variables are non-negative, and constraint (.6) defines the depreciation schedules for durable resources.

In the dynamic optimization model, Eq. (c) is to be minimized:

$$\text{(c)}\quad (1-\tau)\left[\sum_{t\in T}\frac{(P_E^t)(PI_E^t)}{(1+r)^t}+\sum_{t\in T}\sum_{k\in I}\frac{(P_k^t)(PI_k^t)}{(1+r)^t}\right]$$

$$+\sum_{t\in T}\sum_{k\in M}\left[\frac{(\alpha_k^t)(DR_k^t)}{(1+r)^t}-\tau\frac{D_k^t}{(1+r)^t}\right]$$

subject to:

$$(.1)\quad \sum_{k\in K+\tilde{K}}\ \sum_{j\in N_k} a_{ij}^k X_j^{kt} - PI_i^t = 0; \qquad i\in I,\ t\in T$$

(.1a) $\sum_{k \in K+\tilde{K}} \sum_{j \in N_k} a^k_{Ej} X^{kt}_j - PI^t_E = 0; \quad t \in T$

(.2) $X^{kt}_i \leq \sum_{t=0}^{t-1} DR^{kt}_i ; \qquad i \in M, \ t \in T$

(.3) $\sum_{k \in K+\tilde{K}} \sum_{j \in N_k} a^k_{ij} X^{kt}_j = 0; \qquad i \in \tilde{M}, \ t \in T$

(.4) $\sum_{j \in N_k} X^{it}_j \geq R^t_i; \qquad i \in K, \ t \in T$

(.5) $X^{kt}_j \geq 0, \quad PI^t_i \geq 0, \quad DR^t_i \geq 0,$

(.6) $D^t_i = f(DR^t_i, DR^{t-1}_i, \ldots)$, the specified depreciation function.

<u>Glossary</u>

r = cost of capital (discount rate) used by private sector

X^{kt}_j = production of product k, using j^{th} technology, in t

DR^t_i = durable resource investment of type i in t, measured in capacity units

α^t_i = cost/unit of capacity i in t, a function of government policy

τ = corporate tax rate

D^t_i = allowed depreciation for investment in technology i in t

PI^t_i = purchase of non-durable input i in physical quantities in t

P_i^t = price/unit of non-durable input i in t

PI_E^t = purchase of energy inputs in t, in Btu (model accounts for five different energy sources)

P_E^t = price/unit of energy input in t

a_{ij}^{kt} = units of i^{th} purchased input required per unit of j^{th} technology's output for k^{th} process in t

R_F^t = demand for final product F in t; may be price sensitive

Column Sets, indexed on k

$\tilde{K}$ = set of intermediate product activities

K = set of final product activities

I = set of purchased input activities

M = set of purchased durable resource activities

Row Sets, indexed on i

I = set of purchased input constraints

M = set of capacity constraints

$\tilde{M}$ = set of materials balance constraints on intermediate products

K = set of final demand constraints

C. Precedent for the Model

The use of mathematical programming to model the production processes of a firm or an industry was first discussed in the economic literature in 1953 by Dorfman.[7] The first application of mathematical programming to the steel industry appeared in Fabian's article[1] in 1958; since that time, many articles and books describing various programming formulations have appeared,[8-10] and more are on the way.

Why has linear programming been the dominant methodology used to describe the production processes of the industry? The answers lie in the characteristics of the industry and in the particular capabilities of the linear programming models to capture these characteristics relative to the major methodological alternative, econometric modeling.

Econometric modeling has certain characteristics. (1) It is based on statistical analysis of past data. (2) It deals in relations between aggregate measures of behavior (income, price, etc.) leaving to the data themselves the job of describing the actual interplay between technologies. (3) It usually is an equilibrium analysis, depicting the likely relationships between the aggregates after all adjustments and responses have been made. It has certain advantages: it is relatively cheap, since data are usually easily available at the levels of aggregation the models display, it has a long history, and therefore its strengths and weaknesses are well known; and for cases in which the issues addressed require knowledge of the behavior of aggregates (such as employment, income, etc.) it is an "operational" methodology in the sense that both aggregate policy control and variables (Btu taxes, etc.) can be easily adjusted and aggregate policy performance variables (national energy consumption) easily observed. It also has major drawbacks: (1) Technologies are not direct variables in the models in the sense that they can be controlled or observed. (2) It is a "backward looking" approach using past relationships to predict future developments, which is acceptable as long as past and future behavior and experience are not too different; however, when major changes occur in the structure or prices of an industry, or when the industry depends on capital stock that is extremely durable, the long-run past may not reflect the immediate future, and more appropriate methodologies should be used. (3) It generally assumes perfect markets in the factors of production in order to explain behavior, an assumption that is not easy to change.

Process optimization models also have certain characteristics. (1) They deal explicitly with technologies and the competition between them for market shares. (2) The optimization process is explicit in the model, not concealed in its workings. (3) They are generally deterministic (no treatment of uncertainty) and always very data intensive, since explicit representation of all technologies must be entered into the model: it does not "invent" new technologies. (4) The model can capture nonlinearities in relationships to a limited extent, but it cannot successfully represent large-scale systems characterized by increasing returns to scale and fixed charges. Major strengths are (1) the explicit treatment of technologies and optimization, allowing both to be varied, (2) the ability to capture complex interrelationships between activities in an industry, and (3) a high degree of flexibility in treating technology dominated issues. Major weaknesses are (1) difficulty in handling the aforementioned relations, (2) the likelihood that the data required will not be available or reliable, and (3) the large expense of constructing and running the models.

The nature of the iron and steel industry played a dominant role in the selection of process modeling by mathematical programming as the appropriate methodology.

1. The industry is dominated by large, well-known installations (e.g., only about 100 blast furnaces are in operation in the entire U.S.), about which a wealth of data is available as a result of past American Iron and Steel Institute (AISI) data gathering efforts, in some cases going back to 1856 (see AISI Annual Statistical Reports). Furthermore, the recent confrontations between the steel industry and the Environmental Protection Agency (EPA) over compliance costs and between the industry and the Federal Energy Administration (FEA) over voluntary energy conservation goals has led to a vast outpouring of very detailed engineering-economic data on the processes and their distribution in the industry. Thus, the problem of data availability, a major drawback of process analysis, is not as serious as it might be for other industries or might have been in the past for this one.

2. The industry is composed of processes with a high degree of interconnectedness and complexity; offgases and scrap as well as product move freely between production stages. This interconnectedness requires a systems model to evaluate process change, since the full impact on the system of an adjustment in one process will go well beyond the bounds of the process itself.

3. The industry's high degree of vertical integration puts managers in a position to act on system-wide effects; the span of control within a typical firm stretches from iron ore mining and scrap collection to the production of billets, slabs, blooms, and in some cases, final products.

4. The characteristics of very durable capital stock heavily influence decisions in the industry: the tremendous inertia of the existing multi-billion dollar investment will play a dominant and predictable role in the future of the industry.

4. There is a high degree of substitutability between and within the major processes, and the alternatives are well documented in the open literature.

Thus, the major characteristics of the iron and steel industry - available data, high process substitutability and interconnectedness, vertical integration, well-documented technologies, dominant capital stock - are the very ones which the technique of process optimization requires for successful application.

D. Model Limitations

All modeling efforts have inherent faults and limitations. The iron and steel model is no exception. Interpretation of results should be tempered with consideration of the model's shortcomings. The limitations of the iron and steel model in the areas of methodology, data, and technologies are explicitly stated below.

The model's methodology is normative in assuming that the steel industry behaves as a cost minimizer. To the extent that this industry behaves in a oligopolistic manner, this assumption is unwarranted.

The model is national in scope and does not reflect regional differences, that is, it responds to national steel demands and national average fuel prices. It cannot capture regional production shifts that might occur as a result of regional demand change or differing regional fuel prices. For example, if fuel price differences resulted in production increases in lower-price regions, the incentives for adopting conservation technologies would no doubt be reduced.

Costs used in the model are based on the assumption that the technologies are operated at capacity. In general, one effect of operating at below capacity is an increase in per unit energy requirements. For example, in 1975 the industry operated at only 81% capacity and the energy intensity rose to 33.6×10^6 Btu/ton of finished steel, compared with 31.7 for full capacity operation in 1973. Therefore, a healthy industry is a more efficient producer.

As in most models, the severest limitation is the availability of good data. The data used were obtained from the open literature, and in several cases data for new technologies were provided by proponents. For example, the model uses technical characteristics of the blast-furnace coal gasifier provided by its inventor even though the staff of a large steel company disagrees with his evaluation of the technology's potential.

In several cases, "soft" data had to be generated to satisfy the model specifications. For example, scrap price and availability are based on data taken from historical econometric analyses, but enhanced scrap recovery and/or export controls in the future could result in additional energy savings by increasing the scrap supply. The future cost of imported steel is another unknown. Because the model requires that domestic steel demand be met at minimum cost, it calls for importation of steel if production costs are greater than import costs. The model therefore assumes artifically high import prices to guarantee domestic production. However, future energy demand by the domestic steel industry is very sensitive to import levels. Unless a clearly stated policy decision is made, such as imposition of a maximum level of imports, this issue cannot be modeled with any degree of confidence.

Model results are a direct reflection of the technologies assumed. The technologies included in the model are either existing process technologies or energy conserving technologies about which information was taken from the open literature with no access to proprietary information. However, the spectrum of options available to the industry no doubt includes new technologies that are not energy conserving. For example, labor productivity has historically been a more important concern. On the other hand, the considerably lower sensitivity to energy prices in this model than in historical econometric analysis reflects the possibility of considerably more, as yet unspecified, conservation technologies on the horizon.

II. THE INTEGRATED MILL MODEL

The model is presented in 9 sections, each dealing with a major process block in Figure 1 in the Introduction.

A. Iron Ore Mining, Preparation, and Shipment

Because of the variable iron content of different iron ores and the requirement that inputs into the blast furnace have certain physical attributes, iron ore preparation is essential to the iron and steelmaking process.

Before 1960 the bulk of the U.S. iron ores were goethite, limonite, and hemitite, with high (60% Fe) iron content. Depletion of these ores has led to the use of relatively low grade (30% Fe) magnetite-bearing taconite, which is pelletized to increase the Fe content, and increased imports of higher grade iron ore. In 1974, the U.S. imported 35% of the iron ore (60% Fe) needed, 50% of the imports coming from Canada and 33% from Venezuela. About 95% of domestic ores require beneficiation and agglomeration into pellets or sinter having an iron content of 60 to 65% (A.D. Little,[11] p. V-1).

As many investigators have pointed out, this gradual exhaustion of domestic ore reserves will have a profound effect on energy use in the iron and steel industry, since the higher cost per ton iron equivalent of imported ore and pellets will alter the cost-minimizing hot iron/scrap ratio. The model includes two import options: pellets and ore concentrates. Pellets (63% Fe) are assumed to arrive at lower lake ports at a 1975 delivered price of $30.00/ton (Min. Yrbk;[12] p. 727). The 1975 price of ore concentrates (51.5% Fe) is assumed to be $18.75/ton. All imported ores are assumed to be sent by rail to the mills (assumed to be in the Pittsburgh area) at a 1975 price of $4.62 per ton (based on 25% escalation in rail costs since 1973). The only domestic energy charge is the Btu requirement for this transportation, estimated at $0.08x10^6$ Btu/ton-mile by Battelle[13] (p. A-4).

Domestic ore production has the same two forms, pellets, and concentrates. Energy and materials consumption per ton of pellets is from Battelle[13] (p. A-4) and labor and maintenance costs are from Russell and Vaughan[9]. The consumption patterns per ton of ore concentrates are based on Battelle[13] Tables A-3 and A-5.

Costs for domestic ore activities are based on the same data used to estimate delivered import prices, with a fixed $1.00/ton differential to reflect preference for domestic ore by domestic iron and steel producers.

Ore bodies are exhaustable, and they vary in quality. The U.S. Bureau of Mines estimates that 9000 million tons of high grade ore remain in the U.S. which are minable at or near current costs,[14] and further ore could be obtained only at higher cost. To reflect this, the model distinguishes between three domestic ore types:

a. Ore similar in quality and cost to that now mined; cost per delivered ton is $23.00, and the quantity available is $4500x10^6$ tons.[14]

b. Lower quality ore, costing $38.00 per ton to mine, with $4500x10^6$ tons available.[14]

c. Lowest quality ore, costing $50.00 per ton to mine, with $100,000x10^6$ tons estimated to be available[14] (this constraint is never binding).

Since North American reserves (mainly Canadian taconites) amount to $36,000 \times 10^6$ tons,[14] no constraint is placed on the amount of ore or pellet imports over the 25-year horizon.

Iron ore preparation consists of pelletization, which is done at the mine mouth, and sintering, which takes place at the integrated plant itself. Pelletizing is done at the mine mouth because it leaves a 50 to 65% residue from the crude ore which, if not removed, would make transportation costs prohibitive, and because the pellets' resistance to crushing allows them to be transported over long distances if necessary.

The fuel sources used in the process of pelletization are oil, natural gas, and electricity, with the oil and gas being substitutable depending on availability and price. According to Battelle[13] (Table A-4), the process uses a total of 1.6×10^6 Btu per ton of pellets for concentration and pelletizing. Inclusion of the ore mining and mine-mouth ore processing in the model is necessary to evaluate the full impact of energy conservation measures, but it raises some Btu accounting problems because mining and ore processing are reported not in SIC 3312 (blast furnaces, steelworks and rolling mills) but in SIC 1011 (iron ore mining). Hence, the energy consumption per ton of steel reported here includes energy that other analyses exclude and is therefore slightly higher. Discrepancies between commonly reported figures and this analysis are noted in the text.

The sintering operation, which is necessary to convert ore fines into chunks suitable for feeding into a blast furnace, is based mainly on data from Russell and Vaughan[9] and the other sources given in Table 2. Current annual sinter capacity is 47 million tons. (EPA,[15] Vol. 1, p. A-5). The inputs to the sinter process are a mix of iron-bearing materials (such as sludge, ore fines, and flue dust), ignition fuels (such as natural gas and coke oven gas and breeze), and oil. Electricity is used for power fans, drive equipment, etc. Agglomeration of iron ore fines is necessary to prevent ascending gas in the blast furnace from discharging the particulates out of the stack. After ignition of the mixture in the sinter plant, combustion causes the agglomerating particles to form a cake (now containing 60% Fe), which is then quenched with water and broken into pieces of about 4-in. diameter for use in a blast furnace.

Table 2
Iron Ore Processing Options

	Sinter production	Pellet production	Ore
Capacity (10^3 tons/yr)	47000.000	70000.000	-
Investment cost, new ($)	-	75.000	-
Limestone (tons)[3]	0.110	-	-
Steam (10^6 Btu)[3]	0.100	-	-
Residual oil (10^6 Btu)[3]	0.070	0.92	0.43
Electricity (10^3 kWh)[4]	0.039	0.093	0.025
Coke oven offgas (10^6 Btu)[3]	1.460	-	-
Labor (man-hours)[3,9]	0.130	0.260	0.13
Oper. + maint. ($)[3,9]	1.00	2.00	1.00
Scrap (tons)[13]	0.12		-
Taconite Ore (tons)	-	3.45	-
Pellets	-	-1.00	-
Sinter Ore	1.05	-	-
Sinter	-1.0	-	-
Concentrates Ore	-	-	1.0
Concentrates	-	-	-1.0

Fuel conserving options in pelletizing and sintering have received little attention because of the small energy consumption relative to that in the iron and steelmaking process. One technique that may be adopted given the scarcity of natural gas is to use coal firing at pelletization plants. Some recent preliminary investigations (A.D. Little,[11] p. V-13) indicate fuel savings on the order of $4x10^{13}$ Btu/yr of oil and natural gas for complete conversion at all pelletizing plants, at a cost of around $3.00/$10^6$ Btu for the coal gasification plant.

Table 2 summarizes the data currently entered in the model for iron ore mining, preparation, and shipment. Superscripts indicate the sources of data used to arrive at the numbers.

B. Coke Production

The destructive distillation of a blend of coals in coke ovens at 1650^o-2000^oF produces a carbonaceous residue known as coke, the primary fuel for blast furnaces, which produce the iron for steelmaking furnaces. The coke supply situation is one of the major problems facing the steel industry.

In the blast furnace a chemical agent is needed to reduce the oxides of iron; this agent is carbon, which is provided by coke. Coke production requires an expensive low-sulfur bituminous coking coal. Since 90% of the U.S. reserves of low-sulfur bituminous coals are not suitable for coking, the scarcity of coking coals is a growing issue. A solution to this perplexing problem has been proposed, but as yet there is no economic method for producing coke from noncoking coal. Of the 10% of U.S. reserves of low-sulfur bituminous coals that are suitable for coking, 80% are located in West Virginia and Kentucky. The optimal blend of coals, as reported by Thermo Electron Corp.,[3] is 60% high-volatile coal and 40% low-volatile coal. At present the average mix is 66% high-volatile, 16% medium-volatile, and 18% low-volatile. If only high-volatile coal were used, the coke would have a porous, weak form rather than the firm, cellular form desired, which is not obtainable from all bituminous coals. Two other desirable properties of coking coals are low ash content (~8.1%) and low sulfur content (~1.3%). Use of coal with high ash and sulfur contents results in added slag in the blast furnace, increased expenditure for coke, and decreased production. Coke consumption is almost directly proportional to output in the integrated steel mill, since the hydrocarbon injectant modes of operation have been eliminated. Another factor contributing to the integrated steel mill's problems is that the utilities are vying for low-sulfur coal because of the scarcity of natural gas and the environmental protection laws.

Coke is made as follows. A preparation facility receives the various coals suitable for coking, pulverizes them, and blends the high-volatile, medium-volatile, and low-volatile coals in the requisite proportions. The crushed coal is transferred to slot ovens on the plant site and charged into by-product coke ovens (so named because they have facilities for recovering by-products such as light oils, tar, ammonia, and coke oven gas). Combustion air is heated in regenerators and mixed with under-fire fuels (of which 40% is recycled coke oven gas) for burning in the combustion chamber. Under normal operating conditions, the charge is heated for 14 to 16 hr, and then the coke is forced into waiting cars, where it is water-quenched to prevent combustion. A significant portion of the sensible heat is lost here ($\sim 1.4 \times 10^6$ Btu per ton of coke) and could be partly recovered. After cooling, the coke is crushed and screened. Most of it is then transmitted to the blast furnace, and the remaining fines (coke breeze) are conveyed to the reclamation plant and utilized as fuel in the sintering operation. In summary, the outputs of the coke oven are (1) coke, (2) a mixture of H_2 and CH_4 called coke oven gas with a heating value of 500 Btu/ft^3, (3) coke breeze, and (4) light oils and tars.

The primary problems of the steel industry with regard to coke are (1) the dwindling supply of suitable low-sulfur bituminous coking coals, (2) the decreasing quality of the coke, (3) competition by utilities for bituminous coals, and (4) loss of sensible heat in the water-quenching of coke.

The problems of heat loss and decreasing quality can be somewhat ameliorated by a process called dry quenching, which has been used with some success in Europe and the U.S.S.R. and is an option in the model. Dry quenching differs from wet quenching in that the hot coke is dropped into a cooling chamber where by various means combustion is prevented and the coke is cooled, saving $1.2x10^6$ Btu per ton of coke (AISI,[5] p. 28). Capital costs are $123/ton for wet coking (EPA,[15] Vol. 2, exhibit 6), and the cost is $15/ton for retrofitting wet coking to the dry coking process. (average of costs given by AISI[5] and A.D. Little[11]).

Table 3 displays the inputs and outputs for the coke production options in the model, with references.

Table 3
Coke Production Options

	Wet coke	Dry coke
Capacity (10^3 tons/yr)	60000.000	0.0
Investment cost, new ($)	123.000	128.
Coke (tons)	-1.000	-1.00
Steam (10^6 Btu)[3,5]	1.100	-0.1
Residual oil (10^6 Btu)[16]	0.170	0.17
Electricity (10^3 kWh)[5]	0.004	0.01
Coking coal (tons)[16]	1.450	1.45
Labor (man-hours)[5]	0.036	0.06
Oper. + maint. ($)[5]	0.29	0.85
Waste heat (10^6 Btu)	-7.0	-5.8
Coke oven offgas (10^6 Btu)[3]	-6.670	-6.67

C. Blast Furnace

The primary function of a blast furnace is to produce pig iron for introduction into steelmaking furnaces. The manufacture of pig iron requires an input burden which may consist of agglomerated ores (pellets and/or sinter), lumped ores, scrap, and limestone, plus coke to supply carbon monoxide, which combines with the iron oxides to form carbon dioxide and pig iron. The output of a blast furnace is pig iron, slag (formed by combination of limestone with sulfur and other impurities), and an offgas with a heating value of 95 Btu/ft^3. During the production of pig iron (which is tapped every 3 to 5 hr in quantities of 300 to 600 tons), the offgas is consumed in a boiler that produces compressed air via a steam-powered blower. Funneling the air through four or five hot blast stoves provides the heat required in the blast, which is blown in at a temperature of 1200° to 2000°F at the tuyeres near the bottom of the blast furnace. After tapping, the pig iron is transported to the steelmaking furnaces.

Being the largest consumer of energy (41%) in the iron and steelmaking process, the blast furnace has received much attention. The reduction of energy consumption in the blast furnace has been the subject of numerous investigations, but the primary target has been to reduce the per ton use of coke rather than of total Btu. Nominal average values of energy and non-energy inputs to blast furnaces are those provided by Hall et al.,[4] p. 69.

Some ways of lessening the per ton use of coke do not necessarily lower the energy consumption per ton of pig iron produced. Various methods that have been used to reduce coke use are as follows:

1. Installation of new blast furnaces with high top pressures.
2. Improvement of old blast furnaces by retrofitting operations.
3. Increased air-blast temperatures.
4. Optimization of burden.
5. Injection of hydrocarbons.

All these options are included in the model.

1. Higher Top Pressures. Most of the blast furnaces operating today were installed before 1950 and operate with a top pressure of 5 psig. The average coke usage of 1200 lb/ton of pig iron can be reduced by increasing the top pressure. Thermo Electron Corp.[3] reports that at the optimal wind rate savings will amount to 100 lb coke per ton of pig iron. In the design of new

blast furnaces, it is possible to allow for higher top pressures: the Japanese have blast furnaces operating with top pressures as high as 32 psig. Capital costs of such new furnaces are assumed to be a $46/annual ton of capacity.

2. and 3. Retrofitting and Higher Temperatures. Relining and rebricking in existing blast furnaces allows for increased air-blast temperatures; between 1958 and 1968 the average increased from 1230° to 1550°F. Each 100°F increase in blast temperature decreases the coke charge by about 30 lb/ton, and temperatures around 2200°F are considered obtainable with relining at a cost of $5/ton yearly capacity. (Thermo Electron Corp.,[3] p. 5-17).

4. Optimization of Burden. This is most easily achieved by use of bell-less tops which offers three distinct advantages: (a) Coke usage is reduced by 30 lb per ton of pig iron. (b) Capital costs are lower. (c) The burden input mix can be controlled. Capital and installation costs are assumed to be $18 per ton yearly capacity (Thermo Electron Corp.,[3] p. 6-9), although only 15% of existing furnaces can withstand the pressures (AISI,[5] pp. 50, 52). Additional savings might be achieved by installing expansion turbines at a cost of $600 to 700 per kW.

5. Hydrocarbon or Coal Injection. Another means of reducing the coke needed per ton of pig iron is injection of hydrocarbons (mainly natural gas and oil). With 70% of the blast furnaces in the U.S. injecting hydrocarbons, various values of the total Btu impact have been estimated.[17,18] In the present model, a Btu for Btu substitution rate is assumed; this, coupled with the slight Btu loss at the coke plant, means a slight increase in thermal efficiency as hydrocarbons are substituted for coke. However, as the supplies of natural gas dwindle, more steelmaking concerns are attempting to utilize pulverized coal as the main injectant into the blast furnace at the substitutable rate of 0.78 lb coke per lb coal up to 28% of the coke input (A.D. Little,[11] p. VII-4). Retrofit capital costs for the coal pulverizing equipment are assumed to be $6.50 per ton year capacity (AISI,[5] pp. 38,44).

In summary, the scarcity of low-sulfur bituminous coking coals has preempted the search for methods devised primarily to reduce total energy consumption in the blast furnace.

The blast furnace is quite versatile, being able to accept a variety of charges (mixes of scrap, sinter, pellets, lump ore) with little change in performance. Russell and Vaughan[9] specify a wide range of charges on several blast furnace types. In this model only three types of blast furnaces are included:

1. Those built before 1950 (72 million tons per year total capacity) which, because of their limited ability to withstand either high temperatures or high pressures, are allowed only one (low pressure and temperature) mode of operation. For these old furnaces, the nominal input mix given by Hall et al.,[4] p. 69, was modified so that coke input replaced all injectants.

2. Those built after 1950 (47 million tons per year total capacity), which have several options:

a. Choice of burden mix: full pellet, high pellet, high sinter, high ore.

b. Choice of Btu sources: high coke, hydrocarbon injection.

c. High temperature option (requiring relining at a cost of $5.00/ton).

d. Bell-less top option (requiring retrofit; the top itself costing $18/ton).

e. Powdered coal injection (requiring construction of a coal pulverizer at a cost of $6.50/ton).

f. Low-energy-use mode of operation suggested by the International Iron and Steel Institute.[19]

Since not all combinations of the above options are allowed, only 14 combinations appear in the model.

3. The Jordan blast furnace,[20] which is really a coal gasifier with by-product iron produced during operation, which costs $86/ton of annual capacity.

Table 4 lists the options and sources of the data utilized in modeling the blast furnace activity.

D. Direct Reduction

Direct reduction processes are basically of two types, gaseous and solid. The first uses a gas, either hydrogen or carbon monoxide, for removing oxygen from iron; the second usually uses solid carbon. An ideal iron ore for use in a direct reduction process would have an iron content of near 60%. Substantial amounts of this type of ore do exist, and if a run-of-the-mine ore cannot be used, beneficiated ores can.

Table 4
Blast Furnace Options

	IISI	1950	Low ore normal operation	High ore normal operation	Low ore hydrocarbon injection	Medium ore hydrocarbon injection	High ore hydrocarbon injection	Jordan
Invest. cost, new ($)	100.000	-	100.000	100.000	100.000	100.000	100.000	86.000
Coke (tons)	0.400	0.740	0.600	0.600	0.400	0.400	0.400	0.330
Refractory (lb.)	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Scrap (tons)	0.027	0.027	0.027	0.027	0.027	0.027	0.027	0.027
Oxygen (10^3 ft^3)	0.670	0.210	0.210	0.210	0.210	0.210	0.210	11.400
Limestone (tons)	0.230	0.230	0.230	0.230	0.230	0.230	0.230	0.230
Electricity (10^3 kWh)	0.120	0.025	0.025	0.025	0.025	0.025	0.025	0.025
Resid. oil (10^6 Btu)	2.490	-	1.070	1.070	5.430	5.430	5.430	-
Ore (tons)	-	0.410	0.410	1.170	0.200	0.410	1.170	-
Pellets (tons)	1.160	0.760	0.76	-	0.970	0.76	-	1.500
Sinters (tons)	0.500	0.460	0.460	0.46	0.460	0.460	0.46	-
Labor (man-hours)	0.385	0.608	0.452	0.608	0.452	0.452	0.608	0.385
Oper. + maint. ($)	6.540	8.080	4.230	4.230	4.230	4.230	4.230	4.230
Bl. f. offgas (10^6 Btu)	-1.380	-1.840	-1.840	-1.840	-1.840	-1.840	-1.840	-
Coke oven gas (10^6 Btu)	-	-	-	-	-	-	-	-8.700
Steam (10^6 Btu)	1.550	1.550	1.550	1.550	1.550	1.550	1.550	1.550
1973 blast furnace	1.000	-	1.000	1.000	1.000	1.000	1.000	-
Cost ($)	10.000	13.000	0.000	0.000	0.000	0.000	0.000	0.000

	Low ore bell-less top	Low ore high temp.	Medium ore high temp.	High ore high temp.	Low ore pulv. coal	Medium ore pulv. coal	High ore pulv. coal
Invest. cost, new ($)	108.000	105.000	105.000	105.000	106.500	106.500	106.500
Coke (tons)	0.580	0.550	0.550	0.550	0.450	0.450	0.450
Refractory (lb)	5.000	6.000	6.000	6.000	5.000	5.000	5.000
Scrap (tons)	0.027	0.027	0.027	0.027	0.027	0.027	0.027
Oxygen (10^3 ft^3)	0.210	0.210	0.210	0.210	0.210	0.210	0.210
Limestone (tons)	0.230	0.230	0.230	0.230	0.230	0.230	0.230
Steam (10^6 Btu)	1.550	1.550	1.550	1.550	1.550	1.550	1.550
Resid. oil (10^6 Btu)	1.070	1.070	1.070	1.070	1.070	1.070	1.070
Electricity (10^3 kWh)	0.025	0.025	0.025	0.025	0.025	0.025	0.025
Coal (tons)	-	-	-	-	-	0.200	0.200
Ore (tons)	0.410	0.200	0.410	1.170	0.200	0.410	1.170
Pellets (tons)	0.760	0.970	0.76	-a	0.200	0.76	-
Sinters (tons)	0.460	0.460	0.460	0.46	0.970	0.460	0.46
Labor (man-hours)	0.385	0.452	0.452	0.608	0.460	0.452	0.608
Oper. + maint. ($)	4.230	4.230	4.230	4.230	0.452	4.230	4.230
Bl. f. offgas (10^6 Btu)	-1.840	-1.840	-1.840	-1.840	-4.230	-1.840	-1.840
1973 blast furnace	1.000	-	-	-	1.840	-	-
Invest. costs retro. ($)	8.000	5.000	5.000	5.000	6.500	6.500	6.500

Both types of direct reduction process are shown in Figure 1 in the Introduction. The gaseous one is the Midrex process,[21,22] and the solid one is the SL/RN process (SL/RN is an acronym for the four companies that developed it). The product from both processes is 92 to 95% metallized.

Directly reduced iron ore has several advantages:

1. The chemical composition is known exactly.
2. The chemical composition is uniform.
3. It contains no undesirable metallic impurities.
4. It is easy to transport and handle.
5. It allows increased steel furnace productivity.
6. Direct-reduction electric-furnace facilities can be constructed more quickly than those using the coke oven, blast furnace, and basic oxygen.[23]

Some studies[24,25] have shown that for small plants the electric furnace has economic advantages whereas for large plants (>2.5×10^6 tons/yr) it is most economical to construct facilities using the blast furnace and basic oxygen. Of the two types of direct reduction process, the SL/RN which uses coal, is favored in the U.S. because gaseous reductants such as natural gas are becoming more scarce.

In the integrated mill, the Midrex process can be used with pelletized ores of 60% Fe content to obtain a product of 92% metallization (Thermo Electron Corp.,[3] p. 5-6); this requires 1.53 tons of pellets per ton of sponge ore. Fuel consumption is estimated at 12.7×10^6 Btu/ton for the process, and the cost is $92.30 per ton of sponge ore produced.

The model allows sponge ore to be charged to any steel process - electric arc, open hearth, or BOF - even though worldwide practice is restricted to the electric arc or the blast furnace (A.D. Little,[26] p. 61).

In addition, the SL/RN process is available as an option in the mini-mill with coal as the solid reductant; the inputs are based on the references cited plus the cost breakdown by A.D. Little,[26] p. 85.

Table 5 gives the data used for the direct reduction process in the model. Additional capacity, beyond the 3.5 million tons (A.D. Little,[26] p. 85) now in existence, is assumed to cost $140/ton (A.D. Little,[11] p. VII-31).

Table 5
Direct Reduction Options

	Integrated[3]	Mini-mill[26]
Capacity (10^3 tons/yr)	140.00	2000.00
Investment cost, new ($)	-	140.00
Pellets (tons)	1.53	1.50
Flux (tons)	-	0.06
Oxygen (10^3 ft^3)	-	0.10
Oper. + maint. ($)	-	3.00
Labor (man-hours)	-	0.50
Electricity (10^3 kWh)	-	0.51
Coal (tons)	-	0.60
Residual oil (10^6 Btu)	13.00	-
Cost ($)	92.30	-

E. Open-Hearth Furnaces

Before 1970 the mainstay of the iron and steel industry was the open-hearth furnace, but because of economic considerations and the energy crisis, a new workhorse, the basic oxygen furnace, has emerged. In 1973, 55% of the capacity was basic oxygen, 27% was open hearth, and 18% was electric-arc furnaces. The fundamental process in all steel furnaces is the conversion of pig iron and scrap into molten steel via oxidation.

The open-hearth furnace, which consists of a rectangular refractory hearth enclosed by refractory-lined walls and roof, is first charged with scrap plus a small amount of limestone. After the fuel has been ignited and the melting of charge has begun, the proportioned amount of pig iron is charged and high purity oxygen is blown in. After various minor operations, the molten steel is tapped. The total cycle time is 8 to 12 hr. The predominant characteristics of the open-hearth rocess are as follows:

1. It can be charged with up to 100% scrap.
2. It can be retrofitted with the Q-basic oxygen process.
3. The total tap-to-tap time is ~8 hr.
4. Its use is decreasing because of emergence of the basic oxygen process (open hearth output decreased from 100×10^6 tons of raw steel in 1964 to 40×10^6 tons in 1973).

The model has three types of open hearth furnaces (EPA,[15] vol. 1, exhibit A-5):

1. Small relatively old units with 1 million tons/yr of aggregate capacity.

2. Small units built since 1945, amounting to 15 million tons/yr capacity.

3. Large units built since 1945, amounting to 34 million tons/yr capacity.

Energy and non-energy inputs are as reported by Hall et al.,[4] p. 70, with the following exceptions. (1) A high scrap option (0.75 scrap, 0.38 pig iron) is available for all vintages as an alternative to the nominal mix given by Hall et al., (0.51 scrap, 0.62 pig iron). When this option is selected, an additional 0.21×10^6 Btu is assumed necessary to heat the scrap. (2) Oxygen injection is available only in the large units built since 1945, and the addition of 2×10^3 ft^3/ton is assumed to reduce hydrocarbon inputs by 1.4×10^6 Btu/ton. Electricity inputs increase by 143 kWh/ton when this option is used. (3) Nominal electricity, steam (net use minus by-product steam output), use of by-product fuel (coke-oven gas and tars), and natural gas and oil use per ton figures are as reported by Thermo Electron Corp.,[3] p. 4-7. (4) Labor and maintenance costs are as reported by Russell and Vaughan.[9] (5) Offgas, oxygen and waste heat numbers are as reported by the Ford Foundation.[27]

Table 6 gives the data in the model applying to the open-hearth furnace, with the data sources.

New investment in open hearths is allowed in the model at a cost of \$36/ton yearly capacity (EPA,[15] Vol. 2). Early and average open hearths can be converted to Q-BOPs at a cost of \$12.50/ton (Thermo Electron Corp.,[3] p. 5-29) assuming the cost of a Q-BOP is as reported by EPA,[15] Vol. 2.

F. Q-BOP Steel Furnaces

A new process called the Q-basic oxygen process (Q-BOP) had a worldwide capacity of 19 million tons/yr in 1973, of which nearly 9 million tons was in the U. S. (Thermo Electron Corp.,[3] p. 5-32).

The difference between the Q-BOP and the BO processes is that oxygen is blown in at the tuyeres located at the bottom of the Q-BOP furnace. Other notable differences are as follows:

Table 6

Open-Hearth Options

	Early av. scrap	Early high scrap	Average av. scrap	Average high scrap	Best av. scrap	Best high scrap
Invest. cost, new ($)/ton	-	-	-	-	36.000	36.000
Refractory (lb)[4]	40.000	40.000	40.000	40.000	40.000	40.000
Flux (tons)[4]	0.047	0.047	0.047	0.047	0.047	0.047
Lime (tons)[4]	0.013	0.013	0.013	0.013	0.013	0.013
Ferroalloy (tons)[4]	0.101	0.010	0.010	0.010	0.010	0.010
Scrap (tons)[4] (see text)	0.510	0.750	0.510	0.750	0.510	0.750
Oxygen (10^3 ft^3)[27]	1.200	1.200	1.200	1.200	2.000	2.000
Steam (10^6 Btu)[3]	-0.610	-0.610	-0.610	-0.610	-0.610	-0.610
Resid. oil (10^6 Btu)[9] (see text)	2.5	2.7	2.5	2.7	1.1	1.3
Electricity (10^3 kWh)[3]	0.014	0.014	0.014	0.014	0.028	0.028
Labor (man-hours)[9]	0.672	0.672	0.672	0.672	0.672	0.672
Oper. + maint. ($)[15]	19.260	19.260	19.260	19.260	19.260	19.260
Waste heat (10^6 Btu)[2]	-3.600	-3.600	-2.600	-2.600	-1.300	-1.300
Home scrap (tons)[2]	-0.059	-0.050	-0.050	-0.050	-0.050	-0.050
Steel furnace offgas (10^6 Btu)[3]	0.000	0.000	-0.100	-0.100	0.000	0.000
Coke oven offgas (10^6 Btu)[3]	0.760	0.760	0.760	0.760	0.760	0.760
Pig iron (tons)[4] (see text)	0.620	0.380	0.620	0.380	0.620	0.380
Cost ($)	2.490	2.490	1.490	1.490	0.000	0.000

1. The Q-BOP hot metal yield is 2% higher because of less spillage.

2. The Q-BOP has a lower capital cost because it has fewer overhead structure requirements.

3. Q-BOP productivity is 10% higher.

4. The Q-BOP process consumes more energy per ton of raw steel because it requires an additional 168,000 Btu of natural gas per ton (Thermo Electron Corp.,[3] p. 5-32).

The input values in Table 7 reflect the above adjustments to the input figures for the Q-BOP nominal operating values. One energy conserving option, the installation of offgas recovery hoods, is included in the model. It permits the reclamation of 420,000 Btu of offgas per ton of steel at a cost of $5.00/ton annual capacity (Thermo Electron Corp.,[3] p. 6-24; USGS,[14] pp. 69-74). New Q-BOP capacity can be purchased at $20/ton, and old open-hearth

Table 7
Q-Basic Oxygen Options

	Normal operation	With hood for off gas recovery
Capacity (10^3 tons/yr)	9000.000	0.000
Invest. cost, new ($)/ton	20.000	25.000
Refractory (lb)[4]	13.000	13.000
Flux (tons)[4]	0.013	0.013
Lime (tons)[4]	0.075	0.075
Ferroalloy (tons)[4]	0.010	0.010
Scrap (tons)[4]	0.320	0.320
Oxygen (10^3 ft^3)	1.700	1.700
Nitrogen (10 ft^3)[4]	40.000	40.000
Steam (10^6 Btu)[4]	0.020	0.020
Residual oil (10^6 Btu)	0.368	0.368
Electricity (10^3 kWh)[4]	0.030	0.030
Labor (man-hours)[9]	0.280	0.280
Oper. + maint. ($)[9]	3.570	3.570
Home scrap (tons)[28]	-0.050	-0.050
Waste heat (10^6 Btu)[29]	-0.790	-0.370
Steel furnace offgas (10^6 Btu)[29]	-	-0.420
Pig iron (tons)[4]	0.800	0.800
Cost ($)	0.000	0.000

capacity can be retrofitted at $12.50/ton annual capacity, according to Thermo Electron Corp.,[3] p. 5-29.

Table 7 gives the Q-BOP options in the model, with the sources.

G. Basic Oxygen Furnaces

The basic oxygen furnace is very different from the open-hearth furnace. It (BOP or BOF) is a pear-shaped vessel which at the beginning of its cycle is tilted at a 45^{o} angle first to accommodate a scrap charge (up to 30% of the charge) and then to receive the molten pig iron charge. After the ladle is turned upright, high purity oxygen is injected by means of a water-cooled lance located at the top of the vessel. With the melt maintained at 2500^{o} to $2900^{o}F$, chemical reactions take place, after which the molten steel is poured into transfer cars for transportation either to an ingot pouring platform or to a continuous casting machine. The tremendous advantage of the basic oxygen furnace is its total cycle time of 45 min; this results in total cost savings of 12 to 15% over the open hearth despite higher material costs (Kakela,[30] p. 7). With basic oxygen furnaces replacing open hearth at a rapid rate and with the limitations on the amount of scrap that can be charged into a BO furnace, integrated plants are relying on the electric-arc furnace to process the excess scrap. The prevailing characteristics of the basic oxygen furnace are as follows:

1. Increase in output from 17.5% of total steel production in 1965 to 55.5% in 1973 (causing a decrease from 3.2 to 2.3×10^6 Btu per ton of raw steel due to Btu saved in the switch from open hearth).

2. Cycle time of 45 min., which results in a significant increase of output per unit capital compared with open hearth.

3. Better capability for offgas capture in hoods, giving savings of 750,000 Btu per ton of raw steel.

As in the case of other equipment, different vintages of BOPs have different characteristics. The model distinguishes between three vintages: (a) small installations built before 1961, of which units with a million tons/yr capacity are still operating; (b) units built during 1961 to 1968, having 54 million tons/yr capacity; (c) units built since 1968, with 15 million tons/yr capacity.[31]

Several energy saving options are available in the model.

Table 8
Basic Oxygen Options

	Early normal av. scrap	Average preheated high scrap	Average preheated av. scrap	Average preheated low scrap	Average normal av. scrap	Average normal low scrap	Best preheated high scrap	Best preheated av. scrap
Invest. cost, retro. ($)/ton	-	7.500	7.500	7.500	-	-	7.500	7.500
Invest. cost, new ($)/ton	-	-	-	-	-	-	35.000	35.000
Refractory (lb)[4]	13.000	13.000	13.000	-	13.000	13.000	13.000	13.000
Flux (tons)[4]	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
Lime (tons)[4]	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
Ferroalloy (tons)[4]	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Scrap (tons)[4]	0.320	0.450	0.320	0.000	0.320	0.000	0.450	0.320
Oxygen (10^3 ft^3)[4]	1.900	1.900	1.900	1.900	1.900	1.900	1.900	1.900
Nitrogen (10 ft^3)[4]	40.000	40.000	40.000	40.000	40.000	40.000	40.000	40.000
Steam (10^6 Btu)[3]	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
Resid. oil (10^6 Btu)[4]	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Electricity (10^3 kWh)[4]	0.030	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Labor (man-hours)[9]	0.280	0.280	0.280	0.280	0.280	0.280	0.280	0.280
Oper. + maint. ($)[9]	6.130	5.100	5.100	5.100	5.100	5.100	3.570	3.570
Waste heat (10^6 Btu)[32]	-0.790	-0.370	-0.370	-0.370	-0.790	-0.790	-0.370	-0.370
Home scrap (tons)[3]	-0.050	-0.050	-0.050	-0.050	-0.050	-0.050	-0.050	-0.050
Steel furnace offgas (10^6 Btu)[3]	0.000	0.000	-0.420	-0.420	-	-	-	-0.420
Pig iron (tons)[4]	0.800	0.670	0.800	1.120	0.800	1.120	0.670	0.800
Cost ($)	1.330	0.800	0.800	0.800	0.800	0.800	0.000	0.000

Table 8 (cont.)							
	Best Preheated low scrap	Best normal av. scrap	Best normal low scrap	Average hooded av. scrap	Average hooded low scrap	Best hooded av. scrap	Best hooded low scrap
Invest. cost, retro. ($)/ton	7.500	-	-	5.000	5.000	5.000	5.000
Invest. cost, new ($)/ton	35.000	25.000	25.000	-	-	30.000	30.000
Refractory (lb)[4]	13.000	13.000	13.000	13.000	13.000	13.000	13.000
Flux (tons)[4]	0.013	0.013	0.013	0.013	0.013	0.013	0.013
Lime (tons)[4]	0.075	0.075	0.075	0.075	0.075	0.075	0.075
Ferroalloy (tons)[4]	0.010	0.010	0.010	0.010	0.010	0.010	0.010
Scrap (tons)[4]	0.000	0.320	0.000	0.320	0.000	0.320	0.000
Oxygen (10^3 ft^3)[4]	1.900	1.900	1.900	1.900	1.900	1.900	1.900
Nitrogen (10 ft^3)[4]	40.000	40.000	40.000	40.000	40.000	40.000	40.000
Steam (10^6 Btu)[3]	0.040	0.040	0.040	0.040	0.040	0.040	0.040
Resid. oil (10^6 Btu)[4]	0.200	0.200	0.200	0.200	0.200	0.200	0.200
Electricity (10^3 kWh)[4]	0.030	0.030	0.030	0.030	0.030	0.030	0.030
Labor (man-hours)[9]	0.280	0.280	0.280	0.280	0.280	0.280	0.280
Oper. + maint. ($)[9]	3.570	3.570	3.570	5.100	5.100	3.570	3.570
Waste heat (10^6 Btu)[32]	-0.370	-0.790	-0.790	-0.370	-0.370	-0.370	-0.370
Home scrap (tons)[3]	-0.050	-0.050	-0.050	-0.050	-0.050	-0.050	-0.050
Steel furnace offgas (10^6 Btu)[3]	-0.420	-	-	-0.420	-0.420	-0.420	-0.420
Pig iron (tons)[4]	1.120	0.800	1.120	0.800	1.120	0.800	1.120
Cost ($)	0.000	0.000	0.000	0.800	0.800	0.000	0.000

BOF offgas hoods have long been recognized as a possible means of energy conservation. This offgas, whose quality is in the 250 to 300×10^6 Btu/ft^3 range, could be utilized by other processes. For an investment cost of $5.00/ton BOF yearly capacity, an estimated 420,000 Btu/yr can be saved with this option (USGS,[14] p. 70). Currently, 9.8 million tons of BOF capacity have such hoods installed, with an additional 5.8 million expected by 1980.[31]

The possibility of increasing the maximum scrap charge to the BOF by scrap preheaters has been explored as a method of utilizing the same BOF offgases. This would allow integrated mills to retire the open hearths without having to build new electric-arc furnaces to handle the home scrap. Such preheaters can increase BOF scrap charges from 0.32 to 0.45 tons/ton of steel using only the offgases saved by the recovery hoods. (Thermo Electron Corp.,[3] p. 5-26). Estimated costs for this option are $2.50/ton yearly capacity. No operating scrap preheat facilities exist in this country today. The retrofit of existing BOF facilities with such devices is limited in the model to BOFs constructed since 1968. The model allows construction of new BOF facilities with these options; the cost of a new BOF is assumed to be $25/ton of annual capacity (EPA,[15] Vol. 2).

Each BOF vintage has a different set of operating options. Those built before 1961 have only one mode of operation to reflect the limited versatility of these early plants: that given by Hall et al.,[4] p. 71, for the non-energy inputs, and that given by Thermo Electron Corp.,[3] p. 4-6, for the energy inputs. The later two vintages have three options: a low scrap option (100% pig iron charge), a nominal scrap option (0.32 tons/ton), and, with the scrap preheater installed, a high scrap option (0.45 tons/ton). These two vintages can also be retrofitted with hoods to capture the offgases. If the facilities with scrap preheat installations are operated at nominal or low scrap charges, it is assumed that the 420,000 Btu recovered for scrap preheat can be used elsewhere in the mill.

Table 8 gives the model data and data sources for each BOF option.

H. Electric Arc Furnaces

The treatment of electric-arc furnaces in the model is relatively simple. Two vintages are identified: pre-1945 and post-1945 (EPA,[15] Vol. 1). The early ones can produce both carbon and alloy steel, and the later ones can produce carbon, alloy, and stainless steel. An option is available to use the sensible heat in the offgases to preheat the scrap charge for carbon steel only and thus reduce electricity consumption by 15%. Equipment for this can be retrofited on post-1945 furnaces and on all new furnaces; the cost is assumed to be $5.00 per ton of yearly capacity. New electric-arc capacity is available in the model at a cost of $25.00/ton (EPA,[15] Vol. 2).

Electricity consumption per ton in the model depends on both the vintage of the equipment and the type of steel manufactured. Nominal electricity consumption, along with all other inputs, is taken from Hall et al.,[4] p. 72; the rate of 525 kWh/ton is achieved with pre-1945 vintage electric arcs producing carbon steel, and it increases to 740 kWh/ton (Ford,[27] p. 451) with the same vintage furnaces producing alloy and stainless steel. Electricity consumption for the newer, more efficient furnaces is assumed to be 10% lower.

All these data, with sources are summarized in Table 9.

Since electric arcs are used also in mini-mills, the capacity available in 1975 (28 million tons) must be allocated between integrated mills and mini-mills. The only reference to mini-mill electric-arc capacity is given by Thermo Electron Corp.,[3] pp. 3-7 and 1-2, where a capacity of 24 million tons is inferred. The model therefore assumes only 4 million tons of electric arc-capacity available at integrated mills, arbitrarily assigned as 1.8 million tons of pre-1945 vintage, 2 million post-1945, and 0.2 million post-1945 with hoods.

I. Casting, Forming, and Final Finishing

Because various alloys are added during the steelmaking process, the model must distinguish between three types of steel: carbon, alloy, and stainless. All steel furnaces can manufacture carbon steel, but it is assumed that only electric-arc furnaces can produce stainless steel, and only BOFs and electric arcs can produce alloys. (This is not strictly true, since open hearths produced about 1/7 of the total alloy steel made in 1976, AISI,[32] p. 53.) The treatment in the model of carbon steel, alloy, and stainless production is described below.

1. Carbon Steel. After the hot metal leaves the steelmaking furnaces, two major processes remain (i) casting and forming and (ii) final finishing.

Two options are available for the casting and forming stage in the integrated mill model.

Table 9
Electric Arc Options

	Average normal carbon	Best normal carbon	Average normal alloy	Best normal alloy	Best normal stainless	Average hooded carbon
Invest. cost, new ($)/ton	28,000	28.000	28.000	28.000	28.000	33.000
Refractory (lb)[4]	26.000	26.000	26.000	26.000	26.000	26.000
Flux (tons)[4]	0.015	0.015	0.015	0.015	0.015	0.015
Lime (tons)[4]	0.030	0.030	0.030	0.030	0.030	0.030
Ferroalloy (tons)[4]	0.000	0.000	0.010	0.010	0.010	0.000
Scrap (tons)[4]	1.100	1.100	1.100	1.100	1.100	1.100
Oxygen (10^3 ft^3)[4]	0.250	0.250	0.250	0.250	0.250	0.250
Electrodes (lb)[4]	12.000	12.000	12.000	12.000	12.000	12.000
Residual oil (10^6 Btu)[4]	0.100	0.100	0.100	0.100	0.100	0.100
Electricity (10^3 kWh)[4,27,29]	0.525	0.475	0.740	0.660	0.660	0.43
Labor (man-hours)[9]	0.810	0.640	0.810	0.640	0.640	0.810
Oper. + maint. ($)[15]	18.470	18.470	18.470	18.470	18.470	18.470
Waste heat (10^6 Btu)	-0.050	-0.050	-0.050	-0.050	-0.050	-0.020
Home scrap (tons)[15]	-0.050	-0.050	-0.050	-0.050	-0.050	-0.050
Steel furnace offgas (10^6 Btu)[4]	0.000	0.000	0.000	0.000	0.000	-0.030
Cost ($)	1.200	1.200	1.200	0.000	0.000	1.200

Table 10
Integrated Industry Casting Options

	Soak pit carbon	Cont. cast billets carbon	Cont. cast slabs carbon	Cont. cast billets stainless	Cont. cast billets alloy	Soak pit stainless	Soak pit alloy
Ingot casting (tons)[2]	1.020	-	-	-	-	1.020	1.020
Coke oven offgas (10^6 Btu)	0.000	-	-	-	-	-	-
Carbon hot metal (tons)[4]	-	1.040	1.040	-	-	-	-
Stainless hot metal (tons)	-	-	-	1.040	-	-	-
Alloy hot metal (tons)	-	-	-	-	1.040	-	-
Home scrap (tons)[2,4]	-0.020	-0.040	-0.040	-0.040	-0.040	-0.020	-0.020
Dist. oil/gas (10^6 Btu)[4]	1.57	0.510	0.610	0.510	0.510	1.57	1.57
Electricity (10^3 kWh)[4]	-	0.015	0.025	0.015	0.015	-	-
Oxygen (10^3 ft^3)[4]	-	0.560	0.750	0.560	0.560	-	-
Labor (man-hours)[3,15]	0.09	0.0990	0.990	0.990	0.990	-	-
Oper. + maint. ($)[3,15]	1.91	2.470	22.210	2.470	2.470	-	-
Resid. oil (10^6 Btu)[4]	1.57	0.510	0.610	0.510	0.510	1.57	1.57

a. In continuous casting, the hot metal from the steel furnaces is cast directly into billets or slabs (bloom continuous casting is not now available as an option) without loss of the sensible heat. Capacity was 14 million tons in 1972. (EPA,[15] Vol. 1, p. A-5).

b. For ingot casting, the hot metal is allowed to cool and is reheated in soaking pits (usually without recuperator) (Thermo Electron Corp.[3] p. 4-17) with use of offgases generated in prior stages of production; it is then broken into billets, blooms, and slabs suitable for final finishing. Current capacity is 185 million tons (A.D. Little,[11] p. IX-3).

Not all steel can be made by continuous casting (in particular, rimmed low carbon steels) (Thermo Electron Corp.,[3] pp. 5-35, 36). Currently (1974) continuous casting accounts for only 7% (EPA,[15] Vol. 1, p. A-24) of domestic production, even though capacity is much larger. According to A.D. Little,[11] p. VII-2, the technology is already available for continuous casting 50% of steel output. It is reasonable to assume that the technology will be developed to allow continuous casting of all forms of steel within the model's planning horizon. Costs of new capacity are $65 per ton of yearly capacity for billets and blooms and $47 for slabs. (EPA,[15] Vol. 2, exhibit 6).

Table 10 gives the input coefficients, with references, for operation and capacity expansion of the two alternative casting and forming processes.

Semi-finishing (primary hot rolling) is required for the portion of steel production that is ingot-cast and placed in soaking pits, but not for continuously cast steel. Table 11 gives the coefficients associated with semi-finishing for slabs, billets, and blooms.

Table 11
Integrated Industry Semi-Finishing Options

	Carbon blooms	Carbon slabs[15]	Carbon billets[15]	Alloy billets	Stainless billets
Capacity (10^3 tons/yr)	31050.000	80150.000	44260.000	-	-
Invest. cost, new ($)/ton	48.000	47.000	103.000	-	-
Soaking pit (carbon) (tons)	1.160	1.160	1.160	1.25	1.25
Home scrap (tons)	-0.160	-0.160	-0.160	-0.25	0.25
Electricity (10^3 kWh)	0.020	0.038	0.028	0.028	0.028
Labor (man-hours)	0.380	-	0.830	0.830	0.830
Oper. + maint. ($)	4.380	3.490	9.400	9.400	9.400

The final finishing of steel is accomplished in two steps in the model: (1) the reheat step, in which the blooms, slabs, and billets are raised to 1500°F by burning natural gas or oil so that they can be further rolled or milled into finished products, and (2) the final finishing, in which blooms are rolled and milled into heavy structural forms, rails, and pilings; slabs are rolled and milled into plates, sheets, strips, and welded pipes and tubes; and billets are rolled and milled into seamless pipes and tubes, wires, bars, and light structural shapes.

Two options are available for the reheating step: (a) pusher-type reheat furnaces equipped with recuperators to preheat the air to 1000°F, and (b) monobeam furnaces, still under development, which can reduce fuel consumption by 10 to 15%. Table 12 gives the data for the reheating option, with sources.

Current capacities (pusher plus moving beam) are assumed to be 105, 50, and 45 million tons/yr. (A.D. Little,[11] p. IX-3). No production facilities utilizing the monobeam reheat furnace are in operation. Capacity expansion costs in 1976 are $9.42/ton for the pusher type furnace and $7.27/ton for the monobeam (AISI,[5] p. 122). Retrofit costs are substantially lower (A.D. Little,[11] p. IX-7).

The final finishing of steel is distinguished by high scrap losses for blooms, billets, and slabs. Table 13 gives the data and sources. Additional capacity is available at costs of $332, 127, and 194 per ton of yearly capacity for blooms, slabs, and billets respectively (EPA,[15] Vol. 2, exhibit 6).

Some 30 million tons/yr. (50% of slab production) of steel products are annealed, mainly cold-rolled slab products; this requires 1.5×10^6 Btu per ton of product (A.D. Little,[11] p. IX-22). To reflect this use without further complicating the model, it is assumed that all slabs are annealed at 0.75×10^6 Btu/ton rather than half of them at 1.5×10^6.

2. Alloy and Stainless Steel. The model allows stainless and alloy steel billets to be made by continuous casting or ingot casting. The processes are the same as in the case of carbon steel: the data in Tables 10 to 13 do not differ from those for carbon steel, and the references are the same.

Table 12
Integrated Industry Reheating Options

	Moving beam carbon billets	Moving beam carbon slabs	Moving beam carbon blooms	Pusher type carbon billets	Pusher type carbon slabs
Capacity (10^3 tons/yr)[2]	0.000	0.000	0.000	50,000	105,000
Invest. cost, new ($)/ton[2]	6.190	6.190	6.190	6.190	6.190
Semi-finished carbon (tons)[2]	1.020	1.020	1.020	1.020	1.020
Home scrap (tons)[2]	-0.020	-0.020	-0.020	-0.020	-0.020
Dist. oil/gas (10^6 Btu)[2]	2.25	2.25	2.25	2.36	2.36
Electricity (10^3 kWh)[2]	0.000	0.000	0.000	-	-
Steam (10^6 Btu)[3]	0.300	0.300	0.300	0.300	0.300
Residual oil (10^6 Btu)[2]	2.25	2.25	2.25	2.36	2.36

	Pusher type carbon blooms	Pusher type alloy billets	Pusher type stainless billets	Moving beam alloy billets	Moving beam stainless billets
Capacity (10^3 tons/yr)[2]	45,000	*	*	*	*
Invest. cost, new ($)/ton[2]	6.190	-	-	-	-
Semi-finished carbon (tons)[2]	1.020	-	-	-	-
Semi-finished alloy (tons)	-	1.02	-	1.02	-
Semi-finished stainless (tons)	-	-	1.02	-	1.02
Home scrap (tons)[2]	-0.020	-0.02	-0.02	-0.02	-0.02
Dist. oil/gas (10^6 Btu)[2]	2.36	2.36	2.36	2.25	2.25
Electricity (10^3 kWh)[2]	-	-	-	0.0	0.0
Steam (10^6 Btu)[3]	0.300	0.30	0.30	0.30	0.30
Residual oil (10^6 Btu)[2]	2.36	2.36	2.36	2.25	2.25

*Shares capacity with carbon billets

Table 13
Integrated Industry Final Finishing Options

	Carbon billets[15]	Carbon slabs[15]	Carbon blooms[15]	Alloy billets	Stainless billets
Capacity (10^3 tons/yr)[2]	47,000	110,000	15,360	*	*
Invest. cost, new ($)/ton	194.000	127.000	332.000	-	-
Reheated carbon (tons)	1.130	1.280	1.200	-	-
Reheated alloy (tons)	-	-	-	1.13	-
Reheated stainless (tons)	-	-	-	-	1.13
Home scrap (tons)	-0.130	-0.280	-0.200	-0.13	-0.13
Electricity (10^3 kWh)	0.120	0.250	0.170	0.12	0.12
Labor (man-hours)	2.080	2.360	0.370	2.08	2.08
Oper. + maint. ($)	-	-	-	27.14	27.14
Resid. oil (10^6 Btu)	-	0.75	-	-	-
Dist. oil/gas (10^6 Btu)	-	0.75	-	-	-
Steam (10^6 Btu)	1.100	1.100	1.10	1.10	1.10

*Shares capacity with carbon billets

III. THE MINI-MILL INDUSTRY MODEL

Non-integrated mills or mini-mills use steel scrap or directly reduced ore as feedstock, but the scarcity of ores of high iron content has kept mills depending on the latter from flourishing. Mini-mills account for 17% of U.S. capacity (Thermo Electron Corp.,[3] p. 1-2,) and the ratio of mini-mills to integrated mills seems to be growing because of improved technologies for preparing and smelting steel scrap and for using directly reduced ore. A major result of a shift from integrated to mini-mills is that processing waste scrap rather than iron ore may conserve large amounts of fuel. Specifically, to produce a ton of steel from steel scrap requires about half as much fuel as to produce it from iron ore.

The model allows two types of steel, carbon and alloy, to be produced at mini-mills but only one type of product, billets. The first phase of mini-mill steelmaking, the electric-arc furnace, has two options: (a) a 100% scrap charge, like that used in electric arcs in integrated mills, and (b) a charge of 30% directly reduced iron ore and 70% scrap on the basis of Fe content. Data for the direct reduction of ore for the mini-mill (the SL/RN process) plus the two charge options for the electric arc are given in Table 14.

The model allows the carbon or alloy hot metal to be either (a) continuously cast or (b) cast into ingots, put in a soaking pit, and semi-finished. Data for the two alternatives are given in Tables 15 and 16. The sources are the same as those for the integrated mill.

The mini-mill passes the semi-finished steel through either pusher type or monobeam reheat furnaces in preparation for final finishing (Table 17) and then through final finishing (Table 18).

As mentioned in connection with integrated mills, the initial capacity of mini-mills is hard to determine. Thermo Electron Corp. p. 1-2, implies that mini-mill electric-arc capacity is about 24 million tons, the number used in this study; since this is only an estimate, it should be used cautiously. Mini-mill direct reduction capacity is estimated at 2 million tons, and the remaining capacities are set to satisfy the electric-arc furnace output. New capacity for mini-mills can be obtained at the same costs as for integrated mills.

Table 14
Mini-Mill Electric-Arc Options

	Carbon	Alloy	DR* ore carbon	DR* ore alloy
Capacity (10^3 tons)[2]	24,100	**	2,000	**
Invest. cost, new ($)/ton	28.000	28.000	28.000	28.000
Refractory (lb)	26.000	26.000	28.600	28.600
Flux (tons)	0.015	0.015	0.015	0.015
Lime (tons)	0.030	0.030	0.040	0.040
Ferroalloy (tons)	-	0.010	-	0.010
Scrap (tons)	1.100	1.100	0.770	0.770
Oxygen (10^3 ft^3)	0.250	0.250	0.250	0.250
Electrodes (lb)	12.000	12.000	11.000	11.000
Residual oil (10^6 Btu)	0.100	0.100	0.100	0.100
Electricity (10^3 kWh)	0.525	0.74	0.525	0.74
Labor (man-hours)	0.640	0.640	0.640	0.640
Oper. + maint. ($)	18.470	18.470	18.470	18.470
Waste heat (10^6 Btu)	0.860	0.860	0.860	0.860
Home scrap (tons)	-0.050	-0.050	-0.050	-0.050
Steam (10^6 Btu)	1.000	1.000	1.000	1.000
DR* ore (tons)	-	-	0.330	0.330

*DR stands for direct reduction.
**Capacity shared with carbon

Table 15
Mini-Mill Casting Options

	Continuous casting carbon billets	Continuous casting alloy billets
Capacity (10^3 tons)[2]	21,700	*
Carbon (tons)	1.04	-
Alloy (tons)	-	1.04
Homescrap (tons)	-0.04	-0.04
Electricity (10^3 KWh)	0.015	0.015
Oxygen (10^3 ft^3)	0.56	0.56
Labor (man-hours)	0.99	0.99
Oper. + maint. ($)	2.47	2.47
Residual oil (10^6 Btu)	0.51	0.51
Distillate oil/gas (10^6 Btu)	0.51	0.51

*Capacity shared with carbon

Table 16
Mini-Mill Semi-Finishing Options

	Soak pit carbon	Semi-fin. carbon billets	Semi-fin. alloy billets	Soak pit alloy
Capacity (10^3 tons)^2	15,000	15,000	*	*
Ingot casting, carbon (tons)	1.02	-	-	1.02
Soaking pit, carbon (tons)	-	1.16	-	-
Soaking pit, alloy (tons)	-	-	1.16	-
Home scrap (tons)	-0.02	-0.16	-0.16	-0.02
Resid. oil (10^6 Btu)	1.57	-	-	1.57
Dist. oil/gas (10^6 Btu)	1.57	-	-	1.57
Electricity (10^3 kWh)	-	0.028	0.028	-
Labor (man-hours)	0.09	0.830	0.830	0.09
Oper. + maint. ($)	1.91	9.400	9.400	1.91

*Shared with carbon

Table 17
Mini-Mill Reheat Furnace Options

	Pusher type alloy billets	Pusher type carbon billets	Moving beam carbon billets	Moving beam alloy billets
Capacity (10^3 tons)^2	24,000	*	0	0
Semi-finished alloy (tons)	1.02	1.02	-	1.02
Semi-finished carbon (tons)	-	-	1.02	-
Home scrap (tons)	-0.02	-0.02	-0.02	-0.02
Resid. oil (10^6 Btu)	2.36	2.36	2.25	2.25
Dist. oil/gas (10^6 Btu)	2.36	2.36	2.25	2.25
Steam (10^6 Btu)	0.30	0.30	0.30	0.30

*Shared with carbon

Table 18
Mini-Mill Final Finishing Options

	Carbon billets	Alloy billets
Capacity (10^3 tons)^2	24,000	*
Final finishing, carbon (tons)	1.13	-
Final finishing, alloy (tons)	-	1.13
Home scrap (tons)	-0.13	-0.13
Electricity (10^3 kWh)	0.12	0.12
Labor (man-hours)	2.08	2.08
Oper. + maint. ($)	1.10	27.14
Steam (10^6 Btu)	1.10	1.10

*Shared with carbon

IV. ELECTRICITY AND STEAM GENERATION

The model includes 43 options for producing process steam or cogenerating electricity and process steam. All existing boilers are assumed to be nominal cogeneration systems cogenerating electricity at the 1975 average power rate of 9.5 kWh/10^6 Btu steam while existing gas turbines have waste heat boilers operating at a power rate of 220 kWh/10^6 Btu steam. Existing systems include coal, residual oil and natural gas boilers, as well as gas turbines. The integrated mill options include the possible use of blast furnace gas and coke oven gas in assisting the fossil-fueled boilers. New low pressure boilers, boiler/cogeneration sets and gas turbines with waste heat boilers can be purchased for expansion in either integrated mills or mini-mills. These boilers are fueled by coal, residual oil or natural gas. The integrated mill has the option of using blast furnace gas or coke oven gas to assist as boiler fuels. The integrated mill also includes high and low pressure boilers that are fueled by offgases only. New and existing gas turbines can be fueled by natural gas or distillate oil. New gas turbines in integrated mills can also be fueled by coke oven gas. New steam turbine topping equipment generates 42 kWh/10^6 Btu steam, new oil or gas-fired gas turbines with bottoming cycles generate 220 kWh/10^6 Btu steam, and new coke oven gas assisted gas turbines with bottoming cycles are assumed to generate 150 kWh/10^6 Btu steam (Thermo Electron Corp.,[3] p. 6-25).

New and old fossil steam production facilities can be fueled in several ways; Btu consumption per Btu steam production is a function of the amount of electricity produced per Btu steam produced and to some extent of the fuel type. The basic relationship is given by Thermo Electron Corp.,[3] in Figure 5.3, which relates power rate to Btu fuel/Btu steam production. Existing nominal steam turbine topping systems with 9.5 kWh/10^6 Btu steam require 1.30 Btu/Btu steam; new steam turbines with 42 kWh/10^6 Btu steam require 1.53 Btu/Btu steam. If blast furnace or coke oven gas is used, slightly higher Btu requirements are imposed to account for their lower efficiencies.

Gas turbine topping energy use is calculated from the data given by Thermo Electron Corp.[3], Figure 5.5. When distillate oil is used, 220 kWh/10^6 Btu steam is produced, requiring 2.27 x 10^6 Btu of fuel; when coke oven gas is used, 150 kWh/10^6 Btu steam is produced, requiring 2.00 x 10^6 Btu of fuel.

Table 19
Boiler/Cogeneration Options

	Old coal fired	Old coal coke oven gas-fired	Old coal bl. f. gas-fired	Old oil fired	Old oil coke oven gas-fired	Old oil bl. f. gas-fired
Steam (10^6 Btu)	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Electricity (10^3 kWh)	-0.0095	-0.0095	-0.0095	-0.0095	-0.0095	-0.0095
Coal (tons)	0.0524	0.0275	0.0275			
Bl. f. offgas (10^6 Btu)			0.682			0.682
Coke oven offgas (10^6 Btu)		0.682			0.682	
Oper. & Maint. ($)	0.04	0.04	0.04	0.04	0.04	0.04
Resid. oil (10^6 Btu)				1.30	0.682	0.682

	Old coal fired	Old gas coke oven gas-fired	old gas bl. f. gas-fired	Old gas turbine	Old Mini-Mill coal-fired	Old Mini-Mill oil-fired
Steam (10^6 Btu)	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Electricity (10^3 kWh)	-0.0095	-0.0095	-0.0095	-0.22	-0.0095	-0.0095
Coal (tons)					0.0524	
Bl. f. offgas (10^6 Btu)			0.682			
Coke oven offgas (10^6 Btu)		0.682				
Oper. & Maint. ($)	0.04	0.04	0.04	0.45	0.04	0.04
Dist. oil/gas (10^6 Btu)	1.30	0.682	0.682	2.27		
Resid. oil (10^6 Btu)						1.30

	Old Mini-Mill gas-fired	Old Mini-Mill gas turbine	New coal-fired boiler	New coal coke oven gas-fired boiler	New coal bl. f. gas-fired boiler	New coal-fired cogen.
Invest. cost, new ($)			2.00	2.00	2.00	4.60
Steam (10^6 Btu)	-1.0	-1.0	-1.0	-1.0	1.0	-1.0
Electricity (10^3 kWh)	-0.0095	0.22				-0.042
Coal (tons)			0.047	0.025	0.025	0.0617
Bl. f. offgas (10^6 Btu)					0.625	
Coke oven offgas (10^6 Btu)				0.625		
Oper. & Maint. ($)	0.04	0.45	0.01	0.01	0.01	0.073
Dist. oil/gas (10^6 Btu)	1.30	2.27				

Table 19 (Cont'd)

	New Coal coke oven gas-fired cogen.	New coal bl. f. gas-fired cogen	New oil-fired boiler	New oil coke oven gas-fired boiler	New oil bl. f. gas-fired boiler	New oil-fired cogen.
Invest. cost ($)	4.60	4.60	1.11	1.11	1.11	2.51
Steam (10^6 Btu)	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Electricity (10^3 kWh)	-0.042	-0.042				-0.042
Coal (tons)	0.0324	0.0324				
Bl. f. offgas (10^6 Btu)		0.803			0.66	
Coke oven offgas (10^6 Btu)	0.803			1.66		
Oper. & Maint. ($)	0.073	0.073	0.01	0.01	0.01	0.073
Resid. oil (10^6 Btu)			1.25	0.66	0.66	1.53

	New oil coke oven gas-fired cogen.	New oil bl. f. gas-fired cogen.	New gas-fired boiler	New gas coke oven gas-fired boiler	New gas bl. f. gas-fired boiler	New gas-fired cogen.
Invest. cost ($)	2.51	2.51	1.11	1.11	1.11	2.51
Steam (10^6 Btu)	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Electricity (10^3 kWh)	-0.042	-0.042				-0.042
Bl. f. offgas (10^6 Btu)		0.803			0.66	
Coke oven offgas (10^6 Btu)	0.803			0.66		
Oper. & Maint. ($)	0.073	0.073	0.01	0.01	0.01	0.073
Resid. oil (10^6 Btu)	0.803	0.803				
Dist. oil/gas (10^6 Btu)			1.25	0.66	0.66	1.53

	New gas coke oven gas-fired cogen.	New gas bl. f. gas-fired cogen.	New waste-gas-only fired boiler	New waste-gas-only fired cogen.	New gas turbine	New coke oven gas turbine
Invest. cost, new ($)	2.51	2.51	2.00	4.60	5.64	5.64
Steam (10^6 Btu)	-1.0	-1.0	-1.0	-1.0	1.0	-1.0
Electricity (10^3 kWh)	-0.042	0.042		-0.042	-0.22	-0.15
Bl. f. offgas (10^6 Btu)		0.803	0.66	0.84		
Coke oven offgas (10^6 Btu)	0.803		0.66	0.84		2.00
Oper. & Maint. ($)	0.073	0.073	0.01	0.73	0.45	0.45
Dist. oil/gas (10^6 Btu)	0.803	0.803			2.27	

Table 19 (Cont'd)

	New mini-mill coal-fired boiler	New mini-mill coal fired cogen.	New mini-mill oil-fired boiler	Mew mini-mill oil-fired cogen.	New mini-mill gas-fired boiler	New mini mill gas-fired cogen.	Mew mini-mill gas turbine
Invest. cost ($)	2.72	4.60	1.50	2.51	1.50	2.51	11.27
Steam (10^6 Btu)	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0
Electricity (10^3 kWh)		-0.042		-0.042		-0.042	-0.22
Coal (tons)	0.047	0.0617					
Oper. & Maint. ($)	0.01	0.073	0.01	0.073	0.01	0.073	0.45
Dist. oil/gas (10^6 Btu)					1.25	1.53	2.27
Resid. oil (10^6 Btu)			1.25	1.53			

V. ECONOMIC ASSUMPTIONS

An upper limit of 570×10^{12} Btu/yr (1975 actual purchases) of natural gas is assumed, to reflect the increasing scarcity of this fuel to the industry.

A. Cost of Materials - Non-Energy

Table 20 lists the cost of non-energy materials purchased for the first period (1975) of the model, with the data sources.

B. Cost of Materials - Energy

Table 21 gives the assumed energy prices for the five periods (25 years total) now in the model. They are taken from CONAES[33] base case projections based on 1975 actual prices. It is assumed that energy prices will approximately double (relative to other prices) by 2010. The energy content of the fuels not measured in Btu is as follows: for coal, 26.4×10^6 Btu/ton to process, 24.8 in use; for electricity, 10,500 Btu/kWh (in), 3412 Btu/kWh (out).

C. Initial Capacity

The assumptions regarding initial capacities have been discussed in preceding sections of this report, where sources are given; they are summarized in Table 22.

D. Capacity Expansion Costs

Table 23 summarizes the costs for expanding each of the activities represented in the model for both new and retrofit. The reduction in available capacity due to aging of capital stock is handled by applying a decay factor to all existing capacity regardless of its age. The nominal rate in the model is 2%/yr, but it can be adjusted easily by the user. Operation and maintenance costs are not escalated over the lifetime of the equipment because the physical deterioration is accounted for in the decay factor (however, existing older equipment requires more inputs per unit output than newer equipment).

E. Demand Data

Table 24 gives the demand for steel assumed in the model. That for the initial period is 1975 actual demand for finished steel products taken with minor adjustments from AISI.[32]

A 1.5%/yr growth rate was assumed in the base case to drive the model; the mix of steel products was assumed to remain constant over the planning horizon.

F. Scrap Supply Curve

One important consideration in the model is price and availability of scrap material to the steel making industry. Left unconstrained, at current

Table 20
Economic Data (1975)

	Integrated mill cost (dollars/unit)	Mini-mill cost (dollars/unit)
Refractory (lb)[12]	0.058	0.058
Flux (tons)[12]	83.00	83.00
Oxygen (10^3 ft^3)[12]	2.53	2.53
Lime (tons)[12]	27.05	27.05
Ferroalloy (tons)[12]	440.00	-
Scrap, #1 heavy melting (tons)[12]	115.00	100.00
Nitrogen (10 ft^3)[12]	0.09	-
Electrodes (lb)[12]	0.33	0.33
Limestone (tons)[12]	4.45	-
Steam (10^6 Btu)	11.54	11.54
Labor (man-hours)[32]	10.59	10.59
Oper. + maint. ($)	1.00	1.00
*Pellets ore (Taconite)	7.34	-
*Pellet imports (tons)	34.46	34.46
*Ore imports (tons)	23.40	-
*Domestic ore (tons) (prime)	22.40	-
Stainless ingot casting carbon, salbs (tons)	576.9	-
Integrated mill carbon, blooms (tons)	961.54	-
Integrated mill carbon, billets (tons)	961.54	-
Integrated mill carbon, slabs (tons)	961.54	-
Integrated mill alloy (tons)	1153.30	-

*Delivered price, see Section II.A.

Table 21
Energy Prices[33] (dollars/unit)

	Period				
	1	2	3	4	5
Gas (10^6 Btu)	0.96	1.67	2.37	3.08	3.79
Dist. oil (10^6 Btu)	2.36	2.92	3.48	4.04	4.61
Resid. oil (10^6 Btu)	2.02	2.42	2.83	3.23	3.64
Electricity (10^3 kWh)	18.05	20.63	23.21	25.78	28.36
Coal (tons)	29.50	33.71	37.93	42.14	46.36
Coking coal (tons)	44.21	48.42	52.63	56.85	61.07
Sale of elect. (10^3 kWh)	-15.0	-15.0	15.0	-15.0	-15.0
Mini-mill gas (10^6 Btu)	0.96	1.67	2.37	3.08	3.79
Mini-mill dist. oil (10^6 Btu)	2.36	2.92	3.48	4.04	4.61
Mini-mill resid. oil (10^6 Btu)	2.02	2.42	2.83	3.23	3.64
Mini-mill elect. (10^3 kWh)	18.05	20.63	23.21	25.78	28.36
Mini-mill coal (tons)	29.50	33.71	37.93	42.14	46.36

Table 22
Initial Capacities (10^3 Tons)

Integrated mill	
Production of dry coke	0
Production of wet coke	60000
Prod. & consump. of domestic pellets	70000
Prod. & consump. of sinter	47000
Prod. of iron by direct reduction	1100
Blast furnace	
1973	46900
Bell-less top	0
Pulverized coal	0
High temperature	0
1950 vintage year	72000
Jordan	0
Basic oxygen furnace, normal operation	
Early	9000
Average	54000
Best	15000
Basic oxygen furnace, preheated	
Average	0
Best	0
Basic oxygen furnace, hooded	
Average	4500
Best	4500
Q-BOP furnace	
Normal	10000
Hooded	0
Open-hearth furnace	
Early	1000
Average	15000
Best	34000
Electric-arc furnace, normal operation	
Average	1800
Best	2000
Electric-arc furnace, hooded, average	200
Ingot casting	170000
Continuous cast	
Blooms	0
Billets	2400
Slabs	1200

Table 22 (Cont.)

Semi-finishing	
Blooms	31050
Slabs	80150
Billets	44260
Pusher-type	
Blooms	45000
Slabs	105000
Billets	50000
Moving	
Blooms	0
Slabs	0
Billets	0
Final finishing	
Blooms	15360
Slabs	110000
Billets	47000
*Oil boilers	
Using coal	158000
Using oil	72000
Using gas	131000
Gas turbine	15000
Mini-mill	
Electric arc	24000
Gas turbine	15000
Oil-fired boilers	13000
Coal-fired boilers	28000
Gas-fired boilers	23000
Direct reduction	2000
Continuous cast, billets	21700
Final finishing, billets	24000
Pusher type, billets	24000
Moving beam, billets	0
Ingot casting	15000

*Boiler capacity is in units of 10^9 Btu steam.

Table 23
Capacity Expansion Investment Costs ($/ton or $/$10^6$ Btu Steam)

Dry coke	138.00
Wet coke	123.00
Pelletizing	75.00
1973 blast furnace	46.00
Jordan	46.00
Best basic oxygen furnace, Normal operation	25.00
Hooded	26.70
Preheated	32.50
Q-BOP furnace, Normal operation	20.00
Hooded	25.00
Best open hearth furnace	86.00
Average electric-arc furnace, hooded	30.00
Best electric arc furnace, normal operation	25.00
Ingot casting	30.95
Continuous cast, Blooms	999.00
Billets	65.00
Slabs	47.00
Semi-finishing, Blooms	48.00
Slabs	47.00
Billets	103.00
Pusher type, Blooms	9.42
Slabs	9.42
Billets	9.42
Moving beam, Blooms	7.27
Slabs	7.27
Billets	7.27
Final finishing, Blooms	332.00
Final finishing, Slabs	127.00
Billets	194.00
New boilers, Using coal	2.00
Using oil	1.11
Using waste	2.00
Gas turbine	5.64
New cogeneration, Using coal	4.60
Using oil	2.51
Using gas	2.51
Using waste	4.60
Mini-mill, gas turbine	11.27
New boilers, Using coal	[illegible]
Using oil	1.50
Using gas	1.50
New cogeneration, Using coal	4.60
Using oil	2.51
Using gas	2.51
Electric-arc	28.00
Direct reduction	140.00
Pusher type, billets	9.42
Moving beam, billets	7.27
Final finishing, billets	194.00
Continuous cast, billets	65.00

prices the model could choose to purchase more scrap than is actually available. Market steel scrap is composed of obsolete scrap and prompt scrap. Obsolete scrap comes from discarded steel-bearing material and its availability depends primarily on past steel production but prompt scrap comes from steel fabrication losses and its supply depends primarily on current steel production.

Table 24
Final Demand for Steel Products (10^3 Tons)

	Period				
	1	2	3	4	5
Stainless billets	757	544	931	1018	1105
Alloy billets	8436	9405	10374	11343	12312
Carbon blooms	7086	7900	8714	9527	10341
Carbon slabs	45804	51065	56326	61586	66487
Carbon billets	17874	19926	21980	24033	26086

Hogan and Koeble[34] describe the present and projected supply of scrap purchased by the U.S. steel industry. From their data, supplemented by conversations with one of the authors, an equation was developed for predicting price-insensitive purchase of scrap:

where

$$T = 9658(1.053)^{t-1975} + 0.0667D$$

T = tons of steel industry purchased scrap,

t = year, and

D = tons of demand for steel products in year t.

Because the prompt scrap component depends on current steel production, the purchased scrap supply is a function of steel demand. In general, scenarios are driven by energy price and steel demand. Therefore, the price-insensitive purchase of scrap (a function of total steel production) is also scenario dependent, and the above equation should be used to maintain consistency within a scenario.

A scrap supply curve can be generated by combining the price-insensitive relation above with the reported supply price elasticity, with the following

1. The above supply equation gives the availability of scrap at the current real price.

2. The long-term price elasticity of the scrap supply is 1.12.[2] (The supply elasticity overstates the increase in availability of scrap for domestic use because a substantial fraction of the additional amount available will go abroad.)

3. The ultimate scrap limit is 60% higher than indicated by the Hogan and Koeble relation.

4. A stepwise linear supply curve with the point elasticity taken as 1.12 is an adequate representation of the scrap supply curve.

Four supply "bins" are used in the model to form the scrap supply curve. The first allows the amount resulting from the Hogan and Koeble price-insensitive supply availability to be purchased at the 1975 real cost of scrap. The other three increase supply availability by 20% for an 18% increase in price according to the elasticity of 1.12.

C. Purchased Scrap Energy Use

Broderick[35] and Kusik and Kenehan[28] recently estimated the energy requirements per ton of various scrap types, and the mix of such types. Their results are given in Table 25. Since the latter work[28] is more comprehensive, including all major scrap types, the figure 0.60×10^6 Btu/ton is used in this study with the caveat that at least one other reputable investigator has arrived at a number twice as large.

Table 25
Direct Energy Requirements and Mixes, Purchased Scrap

Scrap type	Brodrick[35] 10^6 Btu/ton	Brodrick[35] % Mix	Kusik & Kenehan[28] 10^6 Btu/ton	Kusik & Kenehan[28] % Mix
A. Obsolete				
Shredded car	2.4	19.25	1.28	8.7
Guillotine car			0.65	1.4
Non-auto	1.5	35.75	-	
Sheared scrap			0.51	22
Baled scrap			0.72	29
Alligator shear			0.47	10.5
Torch			0.34	13.6
B. Prompt	0.594	45	0.46	
Average	1.26		0.60	

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APPENDIX

Representative Run of the Model, With Scenario Description and Output

B R O O K H A V E N   N A T I O N A L   L A B O R A T O R Y

REPORT

OF

IRON AND STEEL MODEL

****

1979

SCENARIO DESCRIPTION

	PERIOD 1	PERIOD 2	PERIOD 3	PERIOD 4	PERIOD 5
NATURAL GAS CONSTRAINT (E12 BTU)	576.00	576.00	576.00	576.00	576.00
CAPITAL INVESTMENT CONSTRAINT (E6 $)	400.00	435.16	472.00	514.80	561.13
BTU CONSTRAINT (E12 BTU)	10000.00	10000.00	10000.00	10000.00	10000.00
ENERGY PRICES (INCLUDING BTU TAX)					
INTGRATED MILLS					
ELECTRICITY ($/E3KWH)	18.05	20.63	23.21	25.78	28.36
NATURAL GAS ($/E6BTU)	0.96	1.67	2.37	3.08	3.79
DISTILLATE OIL ($/E6BTU)	2.36	2.92	3.48	4.04	4.61
RESIDUAL OIL ($/E6BTU)	2.02	2.42	2.83	3.23	3.64
COAL ($/TON)	29.50	33.71	37.93	42.14	46.36
COKING COAL ($/TON)	44.21	50.51	56.84	63.15	69.48
MINI-MILL					
ELECTRICITY ($/E3KWH)	18.05	20.63	23.21	25.78	28.36
NATURAL GAS ($/E6BTU)	0.96	1.67	2.37	3.08	3.79
DISTILLATE OIL ($/E6BTU)	2.36	2.92	3.48	4.04	4.61
RESIDUAL OIL ($/E6BTU)	2.02	2.42	2.83	3.23	3.64
COAL ($/TON)	29.50	33.71	37.93	42.14	46.36
STEEL DEMAND (E3 TONS)					
CARBON BLOOMS	7086.00	7900.00	8714.00	9527.00	10341.00
CARBON SLABS	45804.00	51065.00	56326.00	61586.00	66487.00
CARBON BILLETS	17874.00	19926.00	21980.00	24033.00	26086.00
ALLOY BILLETS	8436.00	9405.00	10374.00	11343.00	12312.00
STAINLESS BILLETS	757.00	844.00	931.00	1018.00	1105.00
SLAB SALES	3611.00	4026.00	4440.00	4855.00	5270.00

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STEEL PRODUCTION

INTEGRATED INDUSTRY (E3 TONS)	PERIOD 1	PERIOD 2	PERIOD 3	PERIOD 4	PERIOD 5
CARBON BLOOMS	7086.00	7900.00	8714.00	9527.00	10341.00
CARBON SLABS	45804.00	51065.00	56326.00	61586.00	66487.00
CARBON BILLETS	12504.86	12312.88	16970.97	21470.96	26086.00
ALLOY BILLETS	0.00	0.00	0.00	0.00	8.89
STAINLESS BILLETS	757.00	844.00	931.00	1018.00	1105.00
SLAB SALES	3611.00	4026.00	4440.00	4855.00	5270.00
TOTAL	69762.86	76147.88	87381.37	98456.96	109297.89

MINI - MILL (E3 TONS)					
CARBON BILLETS	5369.14	7613.12	5009.33	2562.04	0.00
ALLOY BILLETS	8436.00	9405.00	10374.00	11343.00	12303.11
TOTAL (E3 TONS)	13805.14	17018.12	15383.33	13905.04	12303.11

INDUSTRY TOTAL (E3 TONS)					
CARBON BLOOMS	7086.00	7900.00	8714.00	9527.00	10341.00
CARBON SLABS	45804.00	51065.00	56326.00	61586.00	66487.00
CARBON BILLETS	17874.00	19926.00	21980.00	24033.00	26086.00
ALLOY BILLETS	8436.00	9405.00	10374.00	11343.00	12312.00
STAINLESS BILLETS	757.00	844.00	931.00	1018.00	1105.00
SLAB SALES	3611.00	4026.00	4440.00	4855.00	5270.00
TOTAL	83568.00	93166.00	102765.00	112362.00	121601.00

IMPORTS (E3 TONS)					
CARBON BLOOMS	0.00	0.00	0.00	0.00	0.00
CARBON SLABS	0.00	0.00	0.00	0.00	0.00
CARBON BILLETS	0.00	0.00	0.00	0.00	0.00
ALLOY BILLETS	0.00	0.00	0.00	0.00	0.00
STAINLESS BILLETS	0.00	0.00	0.00	0.00	0.00

CONSUMPTION AND PRODUCTION OF VARIOUS MATERIALS

	PERIOD 1	PERIOD 2	PERIOD 3	PERIOD 4	PERIOD 5
COKE PRODUCTION (E6 TONS)	37.65	32.26	35.39	39.85	40.82
IRON ORE USE (E6 TONS)					
PELLETS	19.40	63.27	57.20	0.00	0.00
SINTER	33.32	19.50	14.02	15.93	2.29
ORE	0.00	0.00	0.00	0.00	0.00
IMPORTED ORE	90.69	64.44	46.34	52.65	7.57
IMPORTED PELLETS	3.00	8.98	48.26	118.16	176.48
TOTAL	146.41	156.20	165.81	186.75	186.34
IRON PRODUCTION (E6 TONS)					
INTEGRATED MILL	72.43	88.75	100.78	113.41	122.64
MINI-MILL	2.00	1.81	0.00	0.00	0.00
TOTAL	74.43	90.56	100.78	113.41	122.64
SCRAP USE (E6 TONS)					
INTEGRATED MILL					
HOME SCRAP	38.47	42.21	47.94	51.64	54.93
PURCHASED SCRAP	10.71	0.00	0.00	0.00	1.17
TOTAL	49.17	42.21	47.94	51.64	56.10
MINI - MILL					
HOME SCRAP	4.50	4.40	3.98	3.60	3.18
PURCHASED SCRAP	12.68	16.23	16.31	14.74	13.04
TOTAL	17.18	20.63	20.28	18.33	16.22
TOTAL	66.35	62.84	68.22	69.98	72.33

POLICY DATA

	PERIOD 1	PERIOD 2	PERIOD 3	PERIOD 4	PERIOD 5
TAXPAYERS COST					
BTU TAX (E6 DOLLARS)	0.00	0.00	0.00	0.00	0.00
INVESTMENT TAX CREDIT (E3 DOLLARS)	60137.26	48272.51	52627.32	180986.23	11946.60
TOTAL GOVERNMENT EXPENSE (SUM OF TYPICAL YEAR FOR EACH OF 5 PERIODS)					
NO DISCOUNT (E6 DOLLARS)	353.97				
15.00 % DISCOUNT (E6 DOLLARS)	120.12				
TOTAL ENERGY PURCHASES (SUM OF TYPICAL YEARS FOR EACH OF 5 YEARS)					
NO DISCOUNT (E12 BTU)	13416.94				
15.00 % DISCOUNT (E12 BTU)	5225.40				

ENERGY PURCHASED BY SIC CODE (E12 BTU)

SIC-1011 IRON ORE	PERIOD 1	PERIOD 2	PERIOD 3	PERIOD 4	PERIOD 5
ELECTRICITY	18.94	61.79	55.85	0.00	0.00
OIL/GAS	17.85	58.21	52.62	0.00	0.00
TOTAL PURCHASED	36.79	120.00	108.47	0.00	0.00

SIC-3312 BLAST FURNACE STEEL WORKS ROLLING + FINISHING	PERIOD 1	PERIOD 2	PERIOD 3	PERIOD 4	PERIOD 5
ELECTRICITY	346.86	395.74	441.64	422.68	124.39
OIL/GAS	676.30	388.74	144.02	130.18	41.52
STEAM	0.00	0.00	0.00	0.00	0.00
COAL	1640.49	1730.25	2032.54	2235.25	2294.14
TOTAL PURCHASED	2663.65	2514.73	2618.20	2788.11	2460.05

TOTAL FOR SIC-1011 AND SIC-3312					
ELECTRICITY	365.80	457.53	497.49	422.68	124.39
DISTILLATE	0.00	0.00	0.00	0.00	0.00
RESIDUAL	118.15	0.00	0.00	0.00	1.47
NATURAL GAS	576.00	446.95	196.64	130.18	40.04
COAL	1640.49	1730.25	2032.54	2235.25	2294.14
STEAM	0.00	0.00	0.00	0.00	0.00
TOTAL PURCHASED	2700.44	2634.73	2726.67	2788.11	2460.05
TOTAL FOR SCRAP	29.47	20.45	20.54	18.57	17.91

(ELECTRICITY CONVERTED AT 10.500 BTU/KWH)

ENERGY CONSUMPTION CHARACTERISTICS (E12 BTU)

PERIOD 1

	OIL/GAS/OFFGAS	COAL	ELEC	STEAM
ORE MINING/PROCESSING	17.85		6.16	0.00
COKE PRODUCTION	-244.72	1441.24	0.51	41.41
SINTER	50.97		4.43	3.33
BLAST FURNACE	121.40	0.00	6.18	112.26
BASIC OXYGEN	10.22	0.00	7.17	2.80
Q-BOP	3.68	0.00	1.02	0.20
ELECTRIC ARC	1.83	0.00	40.70	17.43
OPEN HEARTH	45.65	0.00	2.12	-13.52
STEEL FINISHING	437.55	0.00	65.55	117.27
COGENERATION	249.71	167.57	-30.67	-281.19
PROCESS STEAM	0.00	0.00	0.00	0.00
DIRECT REDUCTION	0.00	31.58	3.48	0.00
OXYGEN PRODUCTION			12.24	

PERIOD 2

	OIL/GAS/OFFGAS	COAL	ELEC	STEAM
ORE MINING/PROCESSING	58.21		20.08	0.00
COKE PRODUCTION	-209.67	1234.78	0.44	35.48
SINTER	29.84		2.60	1.95
BLAST FURNACE	152.19	269.26	7.57	137.57
BASIC OXYGEN	12.31	0.00	8.05	3.15
Q-BOP	12.17	0.00	3.39	0.66
ELECTRIC ARC	2.14	0.00	47.10	20.40
OPEN HEARTH	0.00	0.00	0.00	0.00
STEEL FINISHING	476.54	0.00	72.70	130.74
COGENERATION	316.56	197.57	-59.56	-329.95
PROCESS STEAM	0.00	0.00	0.00	0.00
DIRECT REDUCTION	0.00	28.64	3.15	0.00
OXYGEN PRODUCTION			43.20	

PERIOD 3

	OIL/GAS/OFFGAS	COAL	ELEC	STEAM
ORE MINING/PROCESSING	52.62		18.15	0.00
COKE PRODUCTION	-230.05	1354.84	0.48	38.93
SINTER	21.45		1.87	1.40
BLAST FURNACE	109.43	408.32	8.60	156.22
BASIC OXYGEN	11.13	0.00	7.28	2.84
Q-BOP	20.86	0.00	5.80	1.13
ELECTRIC ARC	1.96	0.00	44.68	18.44
OPEN HEARTH	0.00	0.00	0.00	0.00
STEEL FINISHING	530.14	0.00	80.34	144.21
COGENERATION	290.74	178.59	-65.92	-290.00
PROCESS STEAM	0.00	90.80	0.00	-73.18
DIRECT REDUCTION	0.00	0.00	0.00	0.00
OXYGEN PRODUCTION			60.42	

PERIOD 4

	OIL/GAS/OFFGAS	COAL	ELEC	STEAM
ORE MINING/PROCESSING	0.00		0.00	0.00
COKE PRODUCTION	-259.03	1525.50	0.70	34.83
SINTER	24.38		2.12	1.59
BLAST FURNACE	124.35	457.52	9.68	175.79
BASIC OXYGEN	-9.29	0.00	6.58	2.57
Q-BOP	-4.03	0.00	7.93	1.55
ELECTRIC ARC	1.79	0.00	42.59	16.67
OPEN HEARTH	0.00	0.00	0.00	0.00
STEEL FINISHING	566.18	0.00	87.39	157.67
COGENERATION	371.17	161.43	-87.42	-317.50
PROCESS STEAM	0.00	90.80	0.00	-73.18
DIRECT REDUCTION	0.00	0.00	0.00	0.00
OXYGEN PRODUCTION			67.82	

PERIOD 5

	OIL/GAS/OFFGAS	COAL	ELEC	STEAM
ORE MINING/PROCESSING	0.00		0.00	0.00
COKE PRODUCTION	-265.32	1562.52	1.39	-4.08
SINTER	3.50		0.30	0.23
BLAST FURNACE	17.87	683.35	10.46	190.08
BASIC OXYGEN	-5.65	0.00	5.95	2.32
Q-BOP	-5.04	0.00	9.93	1.94
ELECTRIC ARC	1.61	0.00	40.26	14.75
OPEN HEARTH	0.00	0.00	0.00	0.00
STEEL FINISHING	596.68	0.00	94.01	170.61
COGENERATION	721.48	48.27	-216.80	-375.85
PROCESS STEAM	0.00	0.00	0.00	0.00
DIRECT REDUCTION	0.00	0.00	0.00	0.00
OXYGEN PRODUCTION			94.93	

(ELECTRICITY CONVERTED AT 3413. BTU/KWH)