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Enhancing the effectiveness of the utility energy supply chain in integrated steel manufacturing

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Enhancing the Effectiveness of the Utility Energy Supply Chain in Integrated Steel Manufacturing

Girish Sudhir Bhawe

**Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of**

**Master of Science
in
Industrial Engineering**

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ABSTRACT

Enhancing the Effectiveness of the Utility Energy Supply Chain in Integrated Steel Manufacturing

Girish Sudhir Bhawe

The iron and steel industry is energy intensive. The steel industry accounts for 2-3 % of total US energy consumption. The energy costs account for 12-15% of the total cost of manufacturing steel. Cogeneration is done by most of the integrated steel producers for on-site electricity generation. The steel industries use different utility systems, and 90% of the industry uses standard steam boilers, steam turbines and BOP (Basic Oxygen Process). The boilers produce steam which is used for power generation and production processes. The system consumes oil, natural gas and blast furnace gas (BFG) to produce this steam and electricity. It is difficult to modulate the machines and manage the system optimally because the boilers may not react to sudden changes in steam loads and fuel availability. Minimizing the fuel cost is an important issue. This could result in the plant using large quantities of purchased fuel and wasting the free sources of energy; such as the BFG to flare and venting BOP steam.

The utility systems in the steel industry, consisting of boilers and turbines, can be considered as a Supply Chain. The venting of free available energy is a major problem with this “Energy Supply Chain”. The solution to this problem is to integrate and link all the system components so that they react together to control the dynamics of the system.

The aim of this research is to design and develop a simulation model for the utility energy supply chain in the steel industry with the help of collected data and validate the model. This model can be used to analyze different control strategies and for generating control and operating strategy decisions.

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Chapter 1

Introduction

Steel is an integral part of life. The consumption of steel shows the strength of the economy. Today in competition with the materials such as plastic, aluminum, sintered powdered products and composites, steel still remains dominant on both low cost and high tonnage basis. Steel forms an essential raw material for buildings, automobiles and many consumer products. The steel industry uses a few raw materials to produce a large variety of products, thus known as a few-to-many industry.

1.1 The Steel making process

The steel production system includes the mining industries providing raw material inputs of iron ore, coke and limestone; the iron and steel industry itself; steel fabrication industries and the steel scrap-processing industry which collects, separates, cleans and grades the discarded steel scrap for recycling.

Iron and steel making is a complex subject but it can be categorized in to five major groups of activities [23]–

- Coking
- Sintering
- Iron making
- Steelmaking
- Final rolling and finishing

The schematic diagram of the process is as shown in Figure 1.1. Each of these processes are described below.

1.1.1 Coking

This is a process of heating coal in the absence of air thus separating some non-carbon constituents of coal from the product (coke). Coke is about 90% carbon. The non-carbon constituents are water and sulfur which are carried off in a gas stream. This coke is used as fuel and a source of carbon monoxide in the blast furnace [23].

Figure 1.1: Schematic view of iron and steel production [23]

1.1.2 Sintering

In sintering, fine ore particles are agglomerated into a porous mass for charging into the blast furnace. Here heat is applied from the combustion of coke to a mixture of ore and flux charge. Limestone is used as a flux charge. Sintering is used to increase the

efficiency of blast furnaces. It does this by decreasing the dust loss, the coke requirement, and the weight of flux required. The process also helps in making use of iron ore fines and the recovered blast furnace flue dust [23].

1.1.3 Iron making

Molten iron is produced by reduction of iron ore in the blast furnace. The ores and the iron bearing materials are charged from the top of the furnace. Along with this predetermined amounts of limestone and coke are also added. Preheated air is blown into the charge from the bottom of the furnace to burn the coke and the descending mass. The gas, from the burning of coke, reduces the stock of materials as they move in opposite directions. The lime from limestone and other bases in the charge fuses with the acid part of the ores and creates a slag that floats on the molten iron and is removed from the furnace periodically. Thus, iron is removed from the non-metallic part of the ore and from the impurities such as sulfur and manganese. Molten iron is removed from the bottom of the furnace [23].

As the hot air passes through the blast furnace, it is converted into blast furnace gas (BFG). One cubic foot of hot air entering the furnace becomes approximately 1.35 cubic foot of blast furnace gas, as it is discharged from the top of the furnace. This gas is then directed through the cleaning equipment, where it is cooled and cleaned. This is a free source of energy and is used to generate electricity and also used by the stove system.

The hot air blown in the blast furnace is preheated in the stoves. The blast furnace stove heats the air which actually reduces the iron ore to iron. The stove is made up of a combustion chamber and a large mass of refractory bricks. The stove operates in two phases. The first one is the ‘on-gas’ phase, where the bricks are heated by burning the blast furnace gas enriched with natural gas in the combustions chamber. The hot exhaust is then passed through the bricks to heat them up. In the second phase the ‘on-blast’ phase, normal air gets heated up as it is forced through heated bricks. This air is then passed to the blast furnace for iron production. A stove that has been heated and is waiting to go ‘on-blast’ is referred to as “Bottled” [26].

1.1.4 Steelmaking

The blast furnace is designed to reduce the iron oxides and to separate the iron from large quantities of impurities in the ore. Steelmaking from molten iron or scrap involves removal of relatively small amounts of certain impurities from the metallic charge through oxidation. Molten iron has impurities such as silicon, manganese, phosphorus and sulfur. These impurities are oxidized and they are removed by solution in furnace slag. There are metallic elements, called tramps, which appear in steel scrap and to a small extent in molten steel which also need to be removed. This process is called tramp-dilution. The hot metal from the blast furnace is charged with a range of scraps. The proportion of hot metal and total scrap in the charge is constrained to some extent by the furnace type. Total charge quantities are based on requirements for total elemental iron output, allowing for losses in flue dust and slag. The steelmaking can be done by the following processes [23]-

1. The open hearth furnace
2. The basic oxygen furnace
3. The electric arc furnace

In the open hearth furnace, a long, shallow charge bath of iron bearing materials is heated by radiation from a flame. The fuel used may be natural gas, coke oven gas, fuel oil, coal tar or a combination of these. Oxygen may or may not be injected. In case of the basic oxygen furnace pure oxygen is introduced from above the surface of the bath of molten iron. Electric power is used as a source of heat in the electric arc furnace. Graphite rods are placed above the cold charge to produce an arc which melts the scrap [23].

1.1.5 Rolling and finishing

In rolling and finishing, the molten steel is converted into semi-finished products. The molten steel is poured into ingot mould, and then allowed to cool and solidify into suitable shapes for further processing. The ingots are then removed from the mould, reheated and rolled in semi-finished shapes. These semi-finished shapes are then converted to finished products by further hot and cold rolling, surface coating and galvanizing [23].

1.2 The Steel Industry Analysis

The steel industry is important for economic competitiveness and national security. The steel industry products are used in all sectors of economy. Steel is used in bridges, automobiles, railroads, skyscrapers and also in appliances. Currently, most of the steel grades used, including high strength steel, are lighter and more versatile than those available 10 years ago. Again, steel is the most recyclable material and has an overall recycling rate of 68 percent [24].

There are more than 1200 firms operating in this sector. The US steel industry is a \$50+ billion enterprise excluding downstream processing, which can push this value up to \$75 billion. The US steel industry is made up of integrated producers and electric arc furnace producers (EAF). Both produce flat-rolled, structural and tubular products. Integrated steel producers produce steel starting from iron ore and coal.

The integrated steel producers have integrated not only the steel making process but also other functions and requirements of the industry. The EAF producers start with scrap steel. They are also called mini-mills. As compared to the integrated steel producers, they have smaller manufacturing costs, and their product range is smaller. They produce lower quality products, particularly bars and structural shapes. Mini-mills are generally more efficient, have better human resources practices and the ability to implement new technology.

In today's scenario, the integrated mills have stopped coke production and are being converted to EAF mills, while some EAF producers have integrated back to iron production and provide complex finishing. Thus the distinction between the two industries has narrowed. The mini-mills have captured the market due to their lower costs and subsequent lower prices, but integrated producers, in response, have shifted to more complex products with higher quality. The integrated steel mills are relatively small in number, currently there are about 20 mills [24].

The steel industry employs about 154,000 people nation-wide and is one of the largest energy consumers in the manufacturing sector. It has invested more than \$7 million in environmental controls.

1.2.1 Economic profile and trends

The steel industry contributes up to 5% of the total US manufacturing GDP. Major transformation has occurred since the recession in the late 1980's. There is investment in new processes and technologies and this has also led to the closing of some mills. Today, the industry employs about 150,000 workers and wages are 50% higher than the average for all US manufacturing sectors. The industry also creates 50,000 additional jobs for down stream processing. The United States produces about 107 million tons of raw steel (1998), which contributes to 13% of the world steel production and thus makes US the largest producer of steel in the world. The US steel industry, still experience acute competition from Asian countries. The industries return on sales is 3% for 1997 as well as 1998. The steel industry economics and trade statistics are shown in the Table 1.1 [24].

Value of shipments	\$75.9 billion
Employment	211,900*
Average hourly wages (Production workers)	\$19.61
Capital Expenditures	\$3.39 billion
R & D Expenditures**	\$414 million
Trade Imports	\$16.1 billion
Trade Exports	\$5.5 billion

* Includes all types of employees in the steel industry and downstream industries related to steel fabrication.

** Includes R&D Expenditures for ferrous metal production and ferrous foundries.

Table 1.1: Industry economic and trade statistic - 1997

The shipments for steel have been increasing steadily since the 1990s. Downsizing and consolidation have reduced the raw steel production by 30% since 1980, but capacity utilization has increased to 90%. Figure 1.2 shows the trends in the value of shipments [24].

Figure 1.2: Value of shipments (1987-1997)

Raw Steel Grade	1998 Production
Carbon	97.0 million tons
Alloy	9.5 million tons
Stainless	2.2 million tons
Total	108.7 million tons

Table 1.2: Annual production – 1998

Table 1.2 shows the annual production of steel in 1998 [24]. About 60 million tons were produced by the basic oxygen furnace process and the remaining 50 million by electric arc furnace process. The major products of the steel mill were sheets, bars, rods, plates, structural shapes, and strips.

The man hours required for producing a ton of steel has been reduced from 10 to less than 4. This 60% drop is basically due to the new processes and technologies, new facilities, increased employee training and new product development. As the production processes are now technologically sophisticated, they need skilled workers; consequently unskilled workers are trained and educated. The 1998 hourly earning was \$20.10 and the employment cost per hour including benefits was \$34.57. Figure 1.3 shows the labor productivity as a percent of that in 1987 [24].

Figure 1.3: Labor Productivity (Labor Output per Hour, indexed to 1987)

1.2.2 Energy use in Steel Industry

The steel industry accounts for 2-3 % of total US energy consumption. The energy is used to supply heat and power for the plant operations and also as a raw material in production of blast furnace coke. According to a recent manufacturing energy consumption survey, in 1994 the US steel industry consumed 2 quads (quadrillion Btu or 10^{15} Btu) of energy. This study includes the losses incurred during the distribution, generation, and transmission of electricity. According to the data compiled by the American Iron and Steel Institute, in 1997, 1.8 quads of energy were consumed including the electrical losses. This is about 2.5% of the total domestic energy consumed in the US and about 8% of the manufacturing energy use. Table 1.3 shows the energy usage in the corresponding years [24].

Year	Total Energy used (Trillion Btu's)
1985	1,869
1988	2,067
1991	1,673
1994	1,983

Table 1.3: Total energy used in Steel Industries

The major source of the energy consumed is coal. This accounts for nearly 50% of the energy. The other two major contributors are natural gas and electricity. During the steel making process, there are two by-product fuels generated; the coke oven gas, and the blast furnace gas. These fuels are recovered for steam generation, preheating blast furnace air, and supplying heat to other plant processes. Figure 1.4 shows the energy use by fuel type in the steel industry [24]. The total energy consumed was 1,993 trillion Btus in 1994 including electric losses.

* losses incurred during the distribution, generation, and transmission of electricity
All values are in Trillion Btu's.

Figure 1.4: Energy use by fuel in Steel Industry (1994)

The energy required to reduce iron ore to liquid pig iron in the blast furnace is about 40% of the total energy input to the steel industry. The energy input to the blast

furnace is derived from coke, made from coal in the coke ovens. Supplemental fuels are also used in this process. For process heating, including electric arc furnace and reheating furnaces, 25% of the energy is used. To generate process steam the steel industry uses natural gas and the by-product gases such as coke oven gas and blast furnace gas. For equipment, heat, light and cooling facilities electricity is used.

As stated above, the steel industry can be categorized in different parts. Table 1.4 shows the energy use of major processes for 1997.

Process	% of Total
Sintering	2
Coke making	0
Iron making	39
BOF Steelmaking	3
EAF Steelmaking	13
Casting	3
Boilers	11
Cogeneration	5
Subtotal	77
All other processes (reheating, rolling, finishing, etc)*	24
Total	100

*Taken as the difference between known total industry and known subtotal use

Table 1.4: Energy use by major processes – 1997 [24]

The energy costs account for 12-15% of the total cost of manufacturing steel. In 1994, the steel industry consumed about 9% of the total energy consumed in the manufacturing sector. Figure 1.5 shows the energy expenditures in billions of dollars. The total energy expenditure here is \$6 billions [24].

Figure 1.5: Energy expenditures - 1994

1.2.3 Energy Intensity

The US iron and steel industry has reduced its energy intensiveness by 45% since 1975 by energy conservation measures, and process improvements. The average energy intensity of producing semi-finished steel at integrated mills using basic oxygen furnace (BOF) steelmaking was 20 million Btu/ton and that for the EAF steelmaking was 8 million Btu/ton. Figure 1.6 shows the energy intensity over the period 1985 to 1994. Figure 1.7 shows the trend as a percent of shipments [24].

Figure 1.6: Energy intensity (Btu / \$ shipments)

Figure 1.7: Energy purchases for heat and power as a percent of shipment

1.2.4 Cogeneration

Cogeneration is done by most of the integrated steel producers for on-site electricity generation. This accounts for 10% of the total electricity used by the steel industry. The competitive advantage of cogeneration over purchased electricity is that due to high thermal efficiencies, excess electricity can be sold back to the grid. Figure 1.8

shows the contribution of cogeneration to net use of electricity in dollars. Figure 1.9 shows trends in the cogeneration capacities over years [24].

Figure 1.8: Cogeneration

Figure 1.9: Trend in cogeneration capacity

These cogeneration operations in the steel industry are conventional systems that use steam boilers and steam turbines. Cogeneration is observed in integrated steel plants since they produce a lot of waste gases such as coke oven gas and blast furnace gas. The

mini-mills generally have a low demand for steam and thus most of the cogeneration is observed in integrated steel mills. About 90% of cogeneration activities are in the integrated steel plants.

1.2.5 Energy management activities

To improve energy efficiency, many energy management activities are carried out by the industry. The top four reported activities are purchasing electricity under special rate (time-of-use rates), electricity load control, energy audits, and power factor correction or improvement. About 61% of the steel industry population engages in one of the energy management activities. Table 1.5 lists the energy management activities as reported in 1994 [24].

Activities	% steel industry population	% consumed energy for heat and power
Energy Audits	33.1	67.9
Electricity load control	42.3	68
Power factor correction or improvement	26.1	47.6
Special rate schedule	45.4	77.7

Table 1.5: Energy management activities – 1994

1.3 Need for Research

As stated earlier, the energy for steel production accounts for nearly 2-3% of US energy consumption. Also, it can be seen from Figure 1.4 that natural gas (purchased energy) is one of the major contributors of energy use. The natural gas cost is 20% of the total energy costs. From Table 1.4 it is seen that the boilers consume 11% of the total energy and cogeneration accounts for 5%. Thus the utility energy is an important factor for energy conservation. The steel industries use different utility systems, but as stated earlier 90% use standard steam boilers, steam turbines and BOP (Basic Oxygen Plant). The boilers produce steam which is used for power generation and production processes. The system consumes oil, natural gas, and blast furnace gas (BFG) to produce this steam

and electricity. It is difficult to modulate the machines and manage the system optimally because the boilers may not react to sudden changes in steam loads and fuel availability. Thus, minimizing the fuel cost is a big issue. This could result in, the plant using large quantities of purchased fuel and wasting the free sources of energy; such as the BFG to flare and venting BOP steam. Thus research in this area of the Utility Energy Supply Chain will prove to be very useful for the steel industry for reducing their energy costs and becoming energy efficient.

1.4 The Energy Supply Chain

A “Supply Chain” is a network of facilities and distribution options that performs the function of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers [28]. Supply chains occur in the service as well as manufacturing industries, although the complexity can vary from industry to industry. “Supply chain management” is a strategy through which these different functions can be integrated [28].

Consider an integrated steel manufacturing industry. The utility systems in the steel industry, consisting of boilers and turbines, can be considered as a Supply Chain. The purchased fuel, natural gas, used as a fuel for the boiler is analogous to the procurement of material. In addition to the purchased fuel, the steel industry uses the blast furnace gas as a free form of fuel for the boilers. These fuels are used to generate the high pressure steam, which is the intermediate product, used by the turbines and further converted into low pressure steam, the final product, which is supplied to the Users of this steam. The Users here are the downstream users such as the tin mill, galvanizing mill, etc. In addition, the low pressure steam generated from the BOP (Basic Oxygen Process) process adds up to the final product low pressure steam. The users form the customers of the supply chain. A good operations strategy must be developed so that this “Energy Supply Chain” can be properly integrated so as to optimize the use of purchased fuel and maximize the use of free fuel and free steam from the BOP.

1.4.1 Problems in the Energy Supply Chain

During the production of pig iron large amounts of blast furnace gas and waste heat steam is produced. This is a free source of energy and must be used instantaneously. The blast furnace gas is then used by the boilers to generate steam. Similarly, during steelmaking large amounts of heat are generated, which can be used to generate steam by the waste heat boilers. The free by-product energy is cyclical and dynamic in nature. If not used instantaneously it is lost. To capture the energy, the steel industries have computerized controls on their system components and thus capture about 95% of the by-product energy to generate the steam and electric power. The remaining 5% is still lost to the atmosphere.

In an integrated steel plant, the optimal management of the boilers and the steam distribution system is difficult because of the interaction among the variables. The most important variable among them is the steam production from the waste heat generated in the steel-making. This steam production is cyclical. The steam from the waste heat boilers is then transferred to the accumulators. The steam is released to the low pressure header at 200 psig. The operating practice is that the accumulator is charged up to a set point pressure and the steam is vented to atmosphere if the pressure increases above that. Thus some steam is vented periodically to prevent the overcharging of the accumulator.

The boilers may not react to sudden changes in steam loads. All the boilers can burn either blast furnace gas which is a free fuel (by-product while producing steel) or purchased fuels (natural gas). Presently the amount of steam required (user demand) is higher than what the boilers can produce with the available BFG. Thus the required deficit is filled by the use of natural gas. It is desired to minimize the amount of purchased fuel used by the boilers. It is also observed that there are times when more BFG is produced than that can be consumed by the boilers, thus the BFG must be flared. Most of the flaring occurs during the summer months when the total demand is low, but even when the steam demand is high some BFG is flared due to blast furnace stove bottling the cyclical nature of net BFG production, and the cyclical nature of BOP steam production.

Thus it can be seen clearly that the venting of the low pressure steam and the flaring of the free fuel, BFG, results in the buying of excess natural gas and low energy efficiency. Again, due to the large number of variables involved, it is difficult to define an operating strategy. In the present situation, the management of these machines is not coordinated and this results in wasting free energy. This is a typical problem in the steel industry and is referred to as “Controlling dynamic system fluctuations involving large amount of by-product energy”.

1.4.2 Solution to the problem of the Energy Supply Chain

Even with the computerized controls on the system equipment, some energy is still vented to the atmosphere. This happens because the computer controlled systems function well as stand alone units. The major focus is to make each process a stand alone unit and to add sensors and controls to make the process more efficient. For example, the boiler with new computerized controls makes the boiler process more efficient as it controls the pressure, temperature, fuel flows, etc perfectly. But this boiler is not linked with the blast furnace, from where the fuel for the boiler comes.

The solution to this problem is linking the major complex unit operations to control dynamic system changes. Thus all the system components must be linked together for integrating the process, so that they anticipate dynamic energy fluctuations and make decisions. This will provide a real time communication data flow between different operating units and all of these units react together to control the dynamics of the system. Finally this will result in reducing the vented BFG and the steam from the BOP boilers.

1.5 Solution Approach

Different approaches can be used for solving the above mentioned problem. Mathematical modelling and simulation are widely used by the industries for designing new processes and to improve the operations of the existing processes. Modelling, simulation and optimization are done to reduce the costs, increase the efficiency, to get a greater understanding of the problem, knowledge management and decision support.

Mathematical optimization is used when we try to optimize a characteristic of a process under a given set of conditions. Optimization is that part of mathematics where we find the best solution. To build the model the problem must be expressed in mathematical relationships. After the model is built, it is solved to get a good solution of the problem. Thus optimization is generally used for structured problems. The problem at hand involves many variables and the interactions among them. So modeling such a system with this tool will be complex and time consuming. Such a approach is good only when the model is simple. There will be simple formulas to answer the questions and can be evaluated numerically. In most of the cases, people study models that are complicated thus valid models for them are also complicated. An exact mathematical solution to the problem may not exist.

Knowledge-based systems or expert systems attempt to model or mimic human reasoning (artificial intelligence). The idea behind the development of expert system is to conserve and transfer knowledge from an expert. So, it involves extracting relevant knowledge from the human expert and then the design of rules with the help of computing software which can be used to solve the problem. For the problem faced in the steel industry, in-depth knowledge of the system is not available. And again due to the dynamic nature of the problem, it is not well structured. Thus application of an expert system is not possible in this case.

The main goal here is to integrate all the system components, link them, so that they react to the dynamic fluctuations simultaneously so as to optimize the fuel used and be energy efficient. Dynamic simulation can be used in this case as it accounts for process transients, from initial state to final state. Secondly, simulation is easier to apply than the mathematical methods and also easier to explain to management. Thus the goal of understanding the process and trying to integrate the equipment can be achieved with dynamic simulations. The simulation model, which will mimic the existing situation, can be used to develop new operating strategies and for optimization of fuel and steam management. This simulation model will also help in understanding the energy supply chain. With the help of this model, the collected data can be put to proper use and used to develop knowledge about the system and make it energy efficient.

Without this simulation model it will be very difficult to analyze the system, as for any change it is required to experiment with the actual system. This can be very costly. Also analytical analysis on the variables involved is difficult due to the high interdependency between them. This model will help analyzing the system without disturbing or destroying it and predict its performance for any change.

1.6 Computer simulation

Computer simulation refers to methods for studying a wide variety of models of real-world systems by numerical evaluation using software designed to imitate the system's operation or characteristics, often over time. Practically, simulation is the process of designing and creating a computer model of a real or proposed system for the purpose of conducting numerical experiments to give us better understanding of the behavior of that system for a given set of conditions. Simulation models can be used to model quite complex systems and thus are often the choice for modeling [25].

1.6.1 Different types of simulations

1. Static vs. Dynamic: time is an important element in the dynamic model while it doesn't play an important role in the static simulations.
2. Continuous vs. Discrete: in case of continuous simulation the state of the system can change continuously over time. But in case of discrete simulation the change can occur only at separated points in time. You can combine the elements of both in the model to form mixed-models.
3. Deterministic vs. Stochastic: for deterministic there is no random input on the other hand stochastic models have random input. A model can have variables that are both deterministic and stochastic.

1.6.2 Advantages of simulation

1. Inferences can be drawn about the system without building, disturbing or destroying it.
2. Simulation can be used to design and calibrate a system or for performance determination.

3. Once constructed, the model can be used to analyze different situations.
4. This model can also be used in cases where input parameters are not very clear or are unknown.
5. Results are much cheaper to obtain than experimenting with the actual system.
6. Easier to apply than analytical (mathematical) methods.
7. Easy to explain to management.

1.6.3 Disadvantages of simulation

1. It may hide some critical assumptions.
2. Simulation is not precise. Degree of imprecision cannot be measured.
3. Simulation can be subject to misuse.
4. Complex systems will lead to complex models.

1.7 General simulation procedure

Simulation results from the perception that it can help resolve one or more issues associated with the design of a new system or the modification of an existing system. There are no strict rules for developing a simulation model, but the general recommended guidelines are presented below. This is an iterative process in which each step may not be complete before moving to the next step. The advantage of adapting to this procedure is to ensure that the project is conducted in an organized and timely fashion.

1.7.1 Plan the study

In planning the study, we have to define our objectives as to which are the variables of study, the relationship between the variables, what the sensitivity analyses are and what sort of decision making is required. Here we also identify the constraints that are to be considered for the model. Also, the level of detail, degree of accuracy and the form of the results may be planned. Thus, this step identifies the scope of the study and gives us the purpose and the intended use of the model.

1.7.2 Define the system

With a proper plan, this step will define a conceptual model on which the simulation model will be based. The work of gathering and validating the system information is carried out here. Several factors must be considered while gathering the data. For example identify the cause-and-effect relationship or the conditions under which the data is collected, or deciding for the key important factors, etc. determine the data requirements from appropriate sources and convert this data in useful form for the use by the model.

1.7.3 Building the model

Once the data is collected, model building can be started. The goal here is the valid representation of the system and also to provide a statistical or graphical representation needed to satisfy the objectives. This is a progressive step in which detail is added to the model in stages rather than all at once. Similarly, complexity is also added in stages.

Verification

Once it is defined using the software tool, the model is checked for its correctness. This process of demonstrating that a model works as intended is referred as verification.

Validation

Another check is how closely the model the model reflects the system definition. The process of determining how closely the model corresponds to the real system is referred to as validation.

1.7.4 Conducting experiments

The next step is conducting experiments. Here the designer sets some hypothesis and tests it through simulation. Based upon the results of the simulation the designer draws conclusions for the set hypothesis. The model can be run with different scenarios and the results can be observed for analysis. This can be also used for comparing alternative decisions or for investment analysis.

1.7.5 Analyzing the output

This concerns drawing inferences about the actual system based on the simulation output. The simulation output never identifies the problems, but reports the symptomatic behavior of problems. Extreme caution must be taken when interpreting the simulation results.

1.7.6 Reporting the results

This is the last step where recommendations are made for the improvement in the actual system based on the results of the simulated model. Animation and output charts are extremely useful aids for communication.

1.8 Research Objectives

A large amount of data is collected in industries for performance monitoring or for generating a database. This raw data must be converted into meaningful information and must be presented in a proper format to generate knowledge about the system. This information and knowledge will help the companies to analyze their systems and investment decisions as well as carry out sensitivity analyses for the system. The objective of this research is to convert such raw data into knowledge. The aim of this research is to design and develop a model for the utility energy supply chain in the steel industry with the help of collected data, validate the model, perform some first-level evaluations of different control strategies and evaluate the usefulness of the model in making control and operating strategy decisions. The specific objectives of this research are listed as follows:

1. Gather data from appropriate sources and convert data into useful form for the use by a simulation model.
2. Design and develop a simulation model that is a valid representation of the system and provide graphical representation of the results.
3. Verify and validate the model.
4. Execute the model using varying inputs and analyze the output to develop an operating procedure for the system so as to reduce the loss of energy.

Chapter 2

Literature Review

2.1 Energy conservation measures in steel industry

The US steel industry has reduced its energy consumption over the past few decades. The historical perspective of the energy use in steel industry and how energy consumption was reduced is discussed by Stubbles [1]. It compares average energy consumption figures with good practices. It projects new technologies and further restructuring of the industry to reduce the energy consumption per ton and estimates potential energy savings. The report also estimates the energy consumption in terms of carbon equivalent and carbon dioxide emissions. The report gives a good insight of the energy use and potential energy savings in steel industry.

The actual energies that are consumed in practice for producing liquid steel from scrap and ore are larger than the theoretical minimum energies required to produce it. Fruehan, Fortini, Paxton, Brindle [2] present the absolute minimum energy to produce steel from ore and mixtures of scrap. This gives an insight into the differences in the theoretical and actual energy consumptions and the factors causing the increase in the energy consumption. The energy consumption is also calculated in terms of carbon equivalent. The study does not focus on actual energy consumed but just compares the industry averages with the theoretical minimum.

Most of the iron production in United States is done by smelting iron ore in the Blast Furnaces. The problem with blast furnace iron making is that the furnaces are relatively small as compared to the new ones and thus inefficient. Also, the availability of high grade metallurgical coke is dropping. Thus the iron making is becoming costly. A summary report prepared by Lockwood Greene Technologies [3], is aimed at evaluating alternate iron making process is carried out. An approach for evaluating the processes was designed so as to have a relative comparison of energy consumptions for each process and find out those alternatives which were lowest in cost and environmentally friendly.

The US Department of Energy's (DOE), Office of Industrial Technologies (OIT) also has a "Best Practices" program that works with industries to identify plant-wide

energy conservation opportunities and efficiency improvements. Some of these case studies have shown good energy savings in the steel industry. Few of the “Best Practices” projects are mentioned below.

A project carried out at a steel mill for improving the steam turbine performance [4] shows that by rebuilding the turbine to incorporate the latest steam path technology and using warmer water instead of cold water for boilers feed water make-up the company significantly increased the capacity and the efficiency of the steam turbine system. The project resulted in large annual savings in terms of electricity and natural gas.

An “Energy Optimization Business Team” is formed at a steel plant [5], which identifies and implements projects that save energy and thus improve performance of plant operation. This energy team has implemented a variety of projects for energy savings in areas such as pilots for boilers, insulating steam lines, repairing steam leaks and repairing leaks in compressed air system.

Steelmaking is an energy intensive process. To reduce the high energy costs a large integrated steel plant carried out a project to replace the plants old utility equipment with modern computer controlled system from a central control center. The project focused on upgrading the control system and instrumentation for the utility system [6]. Thus instead of controlling from different locations a central control center was designed which gathered all the information and helped in making optimal decisions with the changes in energy demand patterns. The modernization of controls and central monitoring facility resulted in large energy and cost savings. The project represents the application of new technology by the management and the ability to reduce the energy [7].

2.2 Mathematical programming applications in integrated steel plants

Integrated steel manufacturing is a complex process. Mathematical programming techniques were used in this industry from a long time. There are a number of variables which interact with each other thus decision making is crucial in this case. Thus mathematical programming applications are found in areas of production planning, scheduling, inventory planning, etc.

2.2.1 National steel planning models

A model for analyzing the steel production for United States is presented by Tsao, and Day [8]. Here a process model is developed for national planning of steel production. Using the engineering and metallurgical information a technology matrix is developed, which represents the technology structure. A linear programming model is then developed using this technology matrix, detailed costs and the sales and revenue Figures. The model estimates of intermediate production and input utilization are compared with the industrial statistics for each year from 1955 to 1968. The model gives fairly good results, but has an error in the coking coal production. A correction of this error is presented by Nelson [9].

Anandalingam [10] addresses the issues of investments in environments where the demand is uncertain by defining a stochastic programming process model. The model also considers uncertainty in technology. To incorporate the parameters and the demand uncertainty, the usual process model is extended by modeling it as stochastic linear program. The model is used for strategic planning rather than operational planning and is applied to steel planning in India.

2.2.2 Product-mix optimization models

Determining optimal production level in an integrated steel plant is of prime importance as the profit is not only sensitive to total volume of production but also the product mix. This optimum product mix changes from month to month and is dependent on the mill, furnace availability and the demand. Suboptimal solutions can be developed by experience but do not achieve the level of profit. Thus mathematical programming has a number of applications in this area.

A cost minimization linear programming model was developed by Fabian [11, 12], in which the blast furnace production process is expressed as a set of constraints of a linear programming model. The model optimizes the cost by changing the input selection. The model has four sub-models; one for iron making, one for steel making and one each for rolling and finishing. All the models are then combined to form a master model of

integrated steel plant. All the technological constraints are considered including the capacity balance, material balance, thermal energy balance, etc.

A large scale database model was developed by Fourer with support of American Iron and Steel institute [13]. As this project was not related to any specific company the model developed is a generic model and any steel company could use it by using its own data. The users will only enter and maintain the data with reporting of optimal results. An associated linear program is automatically generated and is solved to obtain the results. As the model is generic it can be also applied to similar industries like coal mining and oil refineries.

2.2.3 Mathematical models for energy in integrated steel plants

The efficient use of energy in iron and steel plants is important as it contributes to 20% of the total operational cost for the plant. Mathematical models have been developed to have an energy efficient operation.

In case of steel plants, some of the processes require a fixed amount of power and this cannot be switched off even in case of a power crisis. So optimal allocation of electrical energy is important for a steel plant. A mathematical model for optimal allocation of the electrical power was developed and implemented in a steel company in India by Sinha, Chandrasekaran, Mitter, Dutta, Singh, Roy, Choudhury, and Roy, P. [14]. A mixed integer linear programming model has been developed which has a profit maximization objective, with energy as a limiting constraint. The model considers marketing constraints, capacities, yield, profitability, routes, energy and oxygen balances. It models an integrated steel plant with blast furnaces, steel melting shops, and primary and finishing mills. The model considers optimal allocation of capacities, optimal allocation of available power and material flow.

In the iron and the steel manufacturing process a lot of by-product gases are generated and they are used as an energy source. Thus these energy sources are free and do not pay additional cost for purchasing them. But because of unbalance between the generation and the consumption of the by-product gases, at time scale, temporal excess or shortage of the gases happen. Not much research work has been reported on optimization of these by-product gas supply and distribution. A mathematical model is formulated by

Jeong, Heui-Seok and Chonghun [15] in which the objective is to minimize the total cost over the planning horizon subject to constraints for using the by-products gases over the purchased fuels. Other constraints are the material balance, the time varying relationship between the generation and the consumption of the byproduct gases, minimum input, energy balance, etc. The cost consists of the fuel cost, various penalty costs and the steam generation benefit.

An optimal energy distribution control method for steel works is proposed by Fukuda, Makino, Suzuki, and Ishida, [16]. Energy demand forecasting and optimization approach is used. ARMAX (Auto Regressive Moving Average and Exogenous variable) is used for the forecasting of energy and gradient descent method is used for the optimization of energy.

2.2.4 Other areas where mathematical programming is used in a steel industry

Different models have been constructed such as blending models which are basically a cost minimizing models with the thermo chemical metallurgical process in the blast furnace, coke ovens iron and steel foundries are expressed as linear constraints for the problem. The solution indicates a minimum cost related input materials.

Similarly mathematical models have been developed for scheduling, inventory and distribution models. Models for optimal ingot sizes, assignment of semi-finished slabs to order, cutting stock optimization models have also been developed. Dutta and Fourer [17], summarize published applications in large steel plants have a record for all the above mentioned models.

2.3 Simulation approach for developing models

A process model of iron and steel industry was developed by Anandalingam [18] and has a particular focus on energy use and conservation possibilities. Monte-Carlo simulation is used where the model parameters are assumed to be stochastic and distributed normally. It considers steel manufacturing with variables and parameters as coal input, iron ore fines, electricity, heat, sinter, etc. It has random variable inputs with known probability distribution. The analysis is carried out by estimating numerically the

probability distribution of the output variables of process model. The process model is made for Indian iron and steel industry.

Another process model used to study the energy use and conservation in the steel industry in India is developed by Anandalingam and Bhattacharya [19]. It simulates the production process by policy simulation. The production process is modeled by a set of interconnected process activities, each of which defines unique relationships between process output and a number of inputs. It analyzes the impact of energy and material use of a combination of different technologies and evaluates the production cost of each technology.

2.4 Utility system management and operational optimization

For many industrial companies the energy and the utilities cost represent a large portion of their operating costs. Thus large companies are now focusing on reducing the energy cost. Also, optimal operation of site utility systems is becoming an important part of any successful business strategy.

An overview of utility system optimization and management is discussed by Dhole, Seillier, Garza [20] from Aspen Utilities. Aspen Utilities is a single tool that allows economic integration of all business processes associated with purchasing, supply and the use of the utilities. The software has a non-linear mixed integer linear optimization capability. The paper discusses the capabilities and the aspects that are supported by Aspen Utilities software. The software is capable of forecasting, production planning, optimization, performance monitoring and investment planning.

A structured approach for steam system improvement is discussed by Eastwood [21]. The reasons and benefits of building a steam system model are presented here. It gives a spreadsheet based system models with a built-in physical properties database, which helps in reducing the operating costs of steam generation and distribution. Two types of models are considered; planning model and optimizer. The planning model evaluates the projects, what if scenarios, while the optimizer automatically switches the equipment on or off to arrive at an optimum.

CHP (Combined Heat and Power) is a term used to describe energy utilities generation and distribution systems in industrial plants. It is all inclusive of – boilers, fire

heaters, steam turbines, gas turbines, expanders etc. To understand the interactions between them, a simulation model of CHP is useful. The development of such CHP model using electronic spread sheet an illustration of its application using a detailed example is given by Kumana [22]. Thus the CHP models can be one of the tools for energy and cost accounting and improving energy efficiency.

2.5 Conclusion

The above literature gives an idea about the work carried out in the area of energy conservation in steel industry and the measures taken towards reducing the energy cost and optimizing the utility resources in steel industry. It can be seen that a lot of research has been carried out in the area of energy conservation in the steel manufacturing process. New technology and use of mathematical models for optimization has helped the iron and steel manufacturing process to be energy efficient. Similarly, various steps have been taken to optimize the utility energy usage. Simulation in this area is restricted to use of mathematical models and spreadsheet. Higher level simulation software is rarely used. No literature was found on the use of simulation as a tool for analyzing and enhancing the utility energy supply chain for steel industry. The higher level simulation software operates by intuitive graphical user interfaces, menu and dialogues. The model is run with a dynamic graphical animation of system components as they move around and change. The advantage of using such software is that, we can get a better understanding of the system in whole without building, disturbing or destroying it. Also, these are easier to explain to the management as well as easier to apply then mathematical models. Such models can then be used for sensitivity analysis, investment decisions and measuring the performance of the system. Thus research in this area will be of immense help to the steel industry for analyzing and improving on their energy efficiency.

Chapter 3

Research Approach

3.1 Steam Distribution Diagram

Integrated Steel industries generate many by-products while producing steel. They generate blast furnace gas and waste heat as by-products during steel production. They have a co-generation plant, which uses the produced blast furnace gas for production of steam. This high pressure steam is used for the following purposes

1. Direct work generation in blast furnace turbo blowers and boiler auxiliary systems.
2. Electric generation in turbines
3. Conversion to distribution pressure steam in a throttling/desuperheater station.

The data was collected from an integrated steel plant. The data collection and corresponding analysis gives a better understanding of the process as well as the current operating practice of the plant.

The system distribution diagram is shown in the Figure 3.1. Most of the steam is distributed at 200 psig to the Users. This steam comes from several sources. The majority of the steam is produced by the high pressure boilers as shown in the diagram. There are five boilers and they produce steam at about 800 psig and 820°F. Boilers #3, #4 and #5 are located near the blast furnace. The units are water tube boilers made by Babcock and Wilcox (B&W). These are older boilers and they have a capacity of 300,000 lbs to 350,000 lbs per hour of steam. These units can run on various fuels including fuel oil, natural gas, and blast furnace gas (BFG). The other two boilers (#101 and # 102) are new and are Foster-wheeler (FW) units. Each of these boilers can produce about 320,000 lbs per hour of high pressure steam. They can run on natural gas and blast furnace gas. All the boilers have a pilot which uses natural gas when burning BFG. Table 3.1 summarizes the boiler data.

Figure 3.1: Steam system diagram

Boiler #	Capacity (KPPH)		Efficiency (%)
	Minimum	Maximum	
3	130	300	68
4	130	300	73
5	220	350	72
101	200	320	76
102	200	320	80

Table 3.1: Boiler Data

In addition to these boilers, there are waste heat boilers at the basic oxygen plant (BOP). These boilers produce steam from the waste heat released during the steel making process. Steam production at these boilers is cyclical and occurs for roughly half of the 45-minute BOP cycle. This can be seen from the Figure 3.2. This steam is fed to an accumulator at pressures ranging from 200 psig to 600 psig. The accumulator consists of two pipes 10 feet in diameter and 120 feet in length. From the accumulators, the steam is fed through a regulator at 200 psig to the low pressure header. This BOP steam accounts for 17% of the total distribution level steam consumption. This can be observed from Figure 3.3.

There are three turbines viz. #8, #6 and #9. The maximum and minimum steam flow rates and their corresponding electric power outputs are shown in the Table 3.2. The #8 turbine is used to relieve pressure from the high pressure header without charging more steam to the low pressure header and generating electricity in the process. The other two turbines are used to feed the low pressure header at 200 psig. The desuperheaters are used only in cases where the turbines #6 and #9 are insufficient to satisfy the demand at the low pressure header.

Turbine	Minimum		Maximum	
	Steam Flow	Generation	Steam Flow	Generation
	(KPPH)	(MW)	(KPPH)	(MW)
6	70	2.5	360-400	12.2-12.6
8	25	2.5	300	28
9	70	1.9	580-600	18-19

Table 3.2: Turbine data

Figure 3.2: BOP steam cycle

Figure 3.3: Percentage LP Steam Available through different sources

The ramp rates for the boilers and the turbines are as in Table 3.3.

	Ramp rates from Min to Max
#3 and #4	2.5 – 5 minutes
#5	1.5 – 3 minutes
#101 and #102	2 minutes
All turbines	10 – 20 seconds

Table 3.3: Ramp rates for boilers and turbines

3.1.1 Fuel Use

All the boilers can burn either blast furnace gas (BFG) which is a free fuel (by-product of producing iron) or purchased fuel (natural gas). The boilers have pilots which consume only natural gas. The pilots consume large amount of natural gas because they are really incinerators for the BFG, which doesn't burn well by itself. Presently the amount of steam required (user demand) is higher than what the boilers can produce with the available BFG. Thus the required deficit is filled by the use of natural gas. The consumption of BFG and natural gas is shown in Figure 3.4. It is desired to minimize the amount of purchased fuel used by the boilers. The monthly BFG use is shown in Figure 3.5. It is also observed that there are times when more BFG is produced than can be consumed by the boilers, thus the BFG must be flared. Most of the flaring occurs during the summer months, when the total demand is low, but even when the steam demand is high some BFG is flared.

Figure 3.4: Boiler fuel use by month

Figure 3.5: Monthly BFG use

3.1.2 Existing conditions

The optimal management of the boilers and the steam distribution is difficult because of the interaction between the variables. The most important variable is the BOP steam production from the waste heat. Figure 3.6 shows the production of BOP steam in kilo-pounds per hour as a function of time (Drum Flow). The steam production is cyclical and it can be observed from the graph that within a span of 22 minutes the steam production goes from zero to well above 1,200,000 lbs/hr and back to zero. The same cycle repeats itself after a span of about 23 minutes.

As stated earlier, the steam from the waste heat boilers is transferred to the accumulator. The accumulator is rated at 1000 psig. The steam is released to the low pressure header at 200 psig through a regulator. The steam flow from the accumulator is shown in the Figure 3.6 (Process Flow). The operating practice is that the accumulator is charged up to 600 psig and the steam is vented to the atmosphere if the pressure increases above 600 psig. Some steam is vented periodically to prevent the overcharging of the accumulator. This can be observed from Figure 3.6 (Vented Steam). The amount of steam production is more than the capacity of the vent. Thus even though the venting starts at 600 psig the steam pressure builds up to about 800 psig in the accumulator.

Figure 3.6: Steam flow rate

As this steam flows into the low pressure header, the steam incoming from the boilers must be reduced. As the pressure in the low pressure header increases, the #6 and #9 turbines generators are backed down. The firing rates of the boilers are simultaneously reduced, but the steam production in the boilers cannot be reduced as fast as the steam flow rate through the turbines; this can be seen from the ramp rates of the boilers and turbines specified earlier. Thus the pressure in the high pressure header increases. The #8 turbine generator acts as a relief valve. This turbine generator is ramped up pulling the excess steam from the high pressure header generating electricity in the process. This turbine takes the steam out of the system that is considered for analysis.

In cases where the steam demand is high and this demand cannot be satisfied by the #6 and the #9 turbine, the desuperheaters are used, which drop the steam pressure from the high pressure conditions to the low pressure conditions. There are several other small condensing turbines available to further smooth out the imbalances, which are not considered in the designed system.

This low pressure steam system serves many users scattered over the plant. Thus this system is also subjected to many load swings. The daily steam production from all the sources is as shown in Figure 3.7.

Figure 3.7: Low pressure steam generation

3.2 Simulation software

A windows based simulation tool was used for developing the model. The simulation software has a “Build” menu with many modules in it. The models are created by completing the necessary build modules selected from this Build menu. Each module consists of various edit tables and dialogue boxes used to supply model information. Edit tables provide direct accesses to model data and consists of records, which consists of fields describing some aspect of the element. A layout window also appears with the graphical tools for placing the modules. A logic builder is also available which provides a quick and powerful way to create valid statements and expressions in logic fields.

Completed models are run using the “Simulation” menu. The model data is automatically checked for consistency and completeness before each simulation begins. The output generator for the software gathers statistics on each of the defined modules. These simulation results are presented in tabular format or graphic format, including histograms, pie charts, plots and bar graphs. Multiple output results can also be compared on the same charts.

3.2.1 Model elements

In building the model, we must define all of the basic modeling elements and a few of the optional ones. Different modeling elements of the software used are:

Locations: They represent fixed places in the system where the entities are routed for processing, storage, or some other activity or decision making. Locations are used to model elements like machines, waiting areas, work stations, queues, and conveyers.

Entities: Anything that the model processes is called an entity. Parts, products, people, paperwork should be modeled as entities. The movement of the entities triggers the model logic.

Arrivals: Anytime new entities are introduced in the system, it is called as arrival. An arrival record is defined by specifying number of entities per arrival, frequency of the arrival, location of their arrival, first time of their occurrence and total occurrences.

Processing: This defines the routing of the entities through the system and the operations that take place at each location they enter. Once the entities have entered the

system, as defined in the arrivals, processing specifies everything that happens to them until they exit the system. It is this module where the model logic is defined.

Resource: This is a person, a piece of equipment, or some other device which is used for any of the following: transporting entities, assisting in performing operations on entities at locations, performing maintenance on entities or locations. Resources can be dynamic, i.e. they can move along a path.

Path Networks: When the resources are modeled as dynamic resources which travel between locations, they follow path networks. Entities moving by themselves between locations also move on a path network if referenced in the move logic of the routing (processing). Multiple entities and resources may share a common path network. The movement along the path network may be defined in terms of time or speed and distance. The path network can be passing or non-passing and consists of nodes connected by path segments. This segments can be unidirectional or bidirectional.

Variables: There two types of variables; global and local. Global variables are place holders defined by the users to represent changing numeric values. Local variables are available only within the logic in which they are defined, while global variables can be referenced anywhere where numeric expressions are allowed in the model. Variables can be either real numbers or integer values and are typically used for decision making or recording information.

To get a good understanding of the above modeling elements, we can relate the actual system element to these model elements. In relation to the model developed for the utility energy supply chain, the boilers, turbines, user, BFG gas generation, etc, are defined as locations as the entities are routed through them for changing the set variables. Steam, high pressure steam and low pressure steam, BFG gas, etc, are modeled as entities as these are the elements which trigger the logic. The user demand, the BFG, and the BOP steam generation are arrivals as these are the elements where new entities will be introduced in the model. Different path networks are defined so that these entities will move between locations, for example, between the boilers and the turbines. Variables are used for recording and observing the performance. For example, in the case of the steam pressure in the low pressure header, a variable is defined which increments or decrements

as the process logic defined in processing. This incrementing or decrementing is triggered by the arrival of any entity in the location where this process logic is defined.

3.3 Logic flow diagram of the model

From the data collection and analysis, the whole system can be considered to be designed to supply low pressure steam to the users. The users are the Tin mill, Blooming mill, Strip Steel and Sheet mill, etc. They are the process steam end users. The whole system is a “User Driven System”. For modeling purposes, this is considered as a “Pull System”. The users will trigger the whole model.

As seen from the logic flow diagram, Figure 3.8, the cumulative User Demand is calculated and the required quantity is pulled from the low pressure header. This movement of steam from the low pressure header to the users will create a pressure drop in the low pressure header. The low pressure header is maintained at 200 psig, thus the turbines or the accumulator will send the steam to the header to maintain its pressure. This can be observed from the logic flow diagram; the model checks whether the steam pressure is below 200 psig. In case the pressure is below 200 psig the model calculates the amount of steam required, considered as “Error”. Preference is given to the steam coming from the waste heat boilers (BOP steam). Thus the model checks the steam availability in accumulator. The steam arriving from the waste heat boiler is routed to the accumulator. The steam is then released to the low pressure header at 200 psig, if the steam in the accumulator is above a certain point, named here as the “charging point”. This level is measured in terms of the quantity of steam in accumulator (KP). If the steam in accumulator is above the “charging point”, which is input to the model, the steam from the accumulator is routed to the low pressure header. In the case when the steam is not available at the accumulator, the turbines are ramped up so as to pull the steam from the high pressure header.

If the “Error” is greater than the steam available in the accumulator, all the available steam is routed to the low pressure header. Again the model will calculate the “Error” and then this required steam will be supplied by ramping up the turbines, as it moves in the loop.

Figure 3.8: Logic Flow Diagram

Figure 3.8: Logic Flow Diagram

Figure 3.8: Logic Flow Diagram

Figure 3.8: Logic Flow Diagram

Figure 3.8: Logic Flow Diagram

Now if the “Error” is smaller than the available steam, only the required amount is routed to the header and the remaining is then accumulated in the accumulator. For the steam in the accumulator, two points are continuously checked, the “charging point” and the “venting point”. As soon as the “charging point” is attained the steam is routed to the low pressure header at 200 psig and the model again checks the low pressure header pressure. In cases where the accumulator holds steam above the specified “venting point”, it vents the low pressure steam to atmosphere. The BOP steam is directly routed to the accumulator as shown in the Figure 3.8.

Whenever the turbines are ramped up to supply the steam to the low pressure header, the model will check whether the “Error” is greater than what the turbines can supply. If it is greater, the desuperheaters will ramp up to supply the excess steam requirement. The turbines in turn will pull the steam from the high pressure header. As in

the case of the low pressure header, the model will now calculate the steam pressure in the high pressure header. This high pressure header is maintained at 800 psig. If the steam pressure is less than the set limit of 800 psig, the boilers are ramped up, to produce more steam. In the case when the steam pressure is more than 800 psig, turbine #8 is ramped up pulling the excess steam from the high pressure header and putting it out of the system under consideration. Thus, turbine #8 acts as a pressure relief valve. At the same time when the turbine #8 is ramped up, the boilers are ramped down so that they put less steam in the high pressure header.

As the turbines ramp down sensing the steam pressure in the low pressure header, the model will calculate the pressure in the high pressure header, check against its set point. And it will react in the same fashion as said earlier.

For the level of the steam generation by the boiler the model calculates the Btu's required for firing at the required level. Due to the ramping up and down of the boilers the fuel requirement is dynamic. The model will continuously calculate the fuel requirement and check whether the available BFG can satisfy the requirement. While modeling, the total amount of fuel required by all the boilers is calculated and compared to the total available BFG. If the requirement is less than the available BFG, the required quantity is routed to the boilers. In cases where the requirement cannot be satisfied by the BFG, natural gas is pulled by the boilers. A separate natural gas location is available for each boiler from which it will pull the required gas. The model will then calculate the total amount of natural gas required. The pilots for the boilers are continuously pulling the required amount of natural gas. When the available BFG is more than the requirement of the fuel, the BFG is flared.

The last part of the logic flow diagram shows the logic for bottling of stoves. The stoves continuously pull BFG. When they are bottled, all the valves of the stoves are closed, and thus the BFG is not consumed. The stoves thus do not pull any BFG if they are bottled. The times when the stoves can be bottled can be specified by the user. This in turn affects the available BFG for the boilers. With each of the process blocks and decision box, a number is associated. This number is used in the Appendix V where the calculations related to the process block or the decision box is shown.

3.4 Developing the Simulation Model

The whole system is designed to supply low pressure steam to the user. Therefore, the user is an important factor in the system. We can consider this as a “User Driven System”. The users will pull the required amount of steam from the low pressure header. In turn the low pressure header will demand steam from the turbines as required. The steam from the waste heat boiler is sent to the low pressure header. The turbines will ramp up or down depending upon the amount of steam required by the low pressure header. In turn, the boilers will ramp up or down depending upon the high pressure header. As the pressure goes above a set limit in the high pressure header, the boilers will ramp down and simultaneously the #8 turbine can ramp up, sending the excess steam in the high pressure header out of the system.

The simulation uses discrete simulation software. The process of steam is a continuous process. To design a continuous process, two major elements are used in the model:

1. The “Pull system”: The simulation software has a “Pull system”. The software describes “Pull system” as a system in which locations produce parts only on down stream demand. There are 2 types of pull systems
 - a. Based on limited buffer or queue sizes
 - b. Based on more distant down stream demand

The first system will send the parts to the location until capacity is available at the location. While the second method requires us to trigger part movement based on down-stream demand.

2. Global variables: Global variables are the place holders defined by the user to represent changing numeric values. These variables can either contain real numbers or integers, including element index values, and are typically used for decision –making and recording information. A global variable can be referenced anywhere in the model.

The entities are integers and most of the variables involved are real. Thus, as the model runs, the software will truncate the real quantities in integer numbers. To overcome this problem, global variables are defined to keep a track

of the dynamics of the system. Thus the entities will move from location to location updating the global variables.

In our model, we say that it is a user driven system, thus the users are the down stream demand and we design it as a “demand pull” system. The arrival (the user steam requirement) at the user will trigger the whole model. This arrival will pull the steam from the low pressure header, which will in turn trigger the turbines. Then, depending up on the steam pulled by the turbine, the pressure in the high pressure header will change and this will trigger the boilers to ramp up or down. The user can be set as random or a deterministic load with some noise. Figure 3.9 shows these concepts.

Figure 3.9: The “Pull System”

From Figure 3.1, it can be seen that the steam arriving from the waste heat boiler is routed to the accumulator and the steam is then released to the low pressure header at 200 psig. This steam will affect the low pressure header and is cyclic in nature. Thus the pressure maintained in the low pressure header is a function of steam from the turbines and steam from the waste heat boilers; with preference for the steam from the waste heat boilers. Thus the amount of steam flowing from the turbine is dependent upon the waste heat steam.

This is accommodated in the model as a “supply push” mechanism. As the BOP goes on, a huge amount of steam is generated independent of user demand at that time. For this event, a separate arrival of the waste heat steam is designed. This arrival cycle is

the same as observed in the normal case. The data collected for the BOP steam is input in the model through arrays. And these array values are the arrivals for the waste heat steam.

This steam arrival is then linked to the accumulator. The accumulator has two set points viz. the charging point and the venting point. The charging point is the set point up to which the steam is accumulated in the accumulator, before it is sent to the low pressure header. And the venting point is the set point above which the accumulator cannot hold any more steam and the steam is vented to the atmosphere. The accumulator is charged until the charging point and then the steam is passed to the low pressure header at 200 psig. When the accumulator has steam above its venting point it will vent the steam to atmosphere.

A variable is defined as the capacity of the accumulator. The capacity is defined in terms of 1000 lbs of steam. The variable is updated as the waste heat steam comes into the accumulator. When it goes above the charging point, the steam is routed to the low pressure header. The relationship between the amount of steam in the accumulator and corresponding pressure is shown in Appendix IV. Similarly a variable is defined for the low pressure header capacity (in terms of 1000 lbs of steam). This variable is continuously maintained so as to have a pressure of 200 psig in the low pressure header. This is a dynamic variable and it gets decremented when the user pulls the required steam and gets incremented when the steam enters the low pressure header (either through turbines or through the accumulator). These concepts are shown in Figure 3.10.

Another variable is assigned which calculates the “error” between the low pressure header variable and set point of 200 psig. Only this error is sent to the header, first preference being to waste heat steam. Thus, if the waste heat steam is more than the “error” the only the “error” is sent and the remaining is accumulated in the accumulator, thus increasing the accumulator related variable. When this accumulator variable moves above the venting point, the steam is vented. Similarly, the venting variable is incremented by the amount more than the venting point and corresponding accumulator variable is decremented by the same amount.

Figure 3.10: The pull system and push system on low pressure side

For the high pressure side, see Figure 3.11, a variable is defined for the amount of steam in the high pressure header. The variable is similar to the one defined in the low pressure header. The variable is incremented as the steam from any of the five boilers is added to it and is decremented as the steam is pulled by the turbines or the desuperheaters. This variable is continuously adjusted to have pressure of 800 psig in the high pressure header. The relationship between the amount of steam in the high pressure header and corresponding pressure is shown in Appendix IV. Whenever the value is exceeded, the steam is pushed through the #8 turbine, incrementing the variable associated with it. Similarly variables are assigned to the #6 and #9 turbines as well as the desuperheaters. These increment and decrement as the steam passes through them and they represent the steam flow rate through them. Low and high set points are induced for these variables; this accommodates the maximum and minimum steam flow through the turbines. Also for each turbine a variable associated with its steam flow is defined, which is a relation between the power generated for a level of steam flow. This accommodates the electric generation for these turbines.

In the case of the boilers, we have two variables associated with each. One indicates the amount of steam generated and the other gives the amount of Btu's required for that level of steam generation. The variable for steam generation is linked to the amount of steam in the high pressure header. A linear relationship is developed such that the boilers

fire at maximum when the pressure moves below the set point and at minimum when the pressure is at the set point. The Btu variable is used for the amount of blast furnace gas (BFG) required. The boilers will pull the BFG as per their requirement from a common location. Limits are put on the variables denoting the steam generation, accommodating the maximum and the minimum firing rates for the boilers.

Figure 3.11: The high pressure side

For the blast furnace gas, data is collected and the amount of blast furnace gas produced is found and is converted into Btu equivalent. This is modeled as a separate location with its arrival. This gas is then routed to the boilers and the stoves. The stoves are given the preference over the boilers, i.e. they are continuously supplied with the BFG and the remaining amount is distributed to the boilers. The BFG is sent to the boilers with the following preference; first to the boiler 101, then 102, then 3 and 4 and 5. If the blast furnace gas is insufficient to satisfy the fuel requirement, natural gas is used. Due to this, boilers 4 and 5 may seem to use more natural gas.

Each boiler has a pilot that uses natural gas. Thus to model the use of natural gas, each boiler is supplied with a separate location denoting a pilot and the pilot is supplied with a separate natural gas reserve. The same gas reserve supplies the boiler with natural gas in cases where the firing levels need more fuel than available BFG. For the arrivals of the natural gas, data is collected and converted to Btu's. Thus the required Btu's for the boilers are satisfied by the Btu's of BFG and the natural gas (if required).

For the case where the level of the BFG is more than required, the BFG is flared. As designed earlier, a variable is defined for the BFG production. If the gas is not utilized completely, the entities are routed to a location 'flaring'. Here the variable is incremented, thus denoting the flaring of BFG, see Figure 3.11.

Another variable is defined for the efficiency of the boilers. The efficiency of a boiler changes as the load changes. It is defined as a step change and a linear relation is obtained for the efficiency. The linear relationship is defined in Table 3.4.

Boiler	Load (KPPM)	efficiency	Relation
101	4.3	65%	$y = 9.375x + 40$
	4.8	75%	
	5.3	80%	
102	4.3	65%	$y = 9.375x + 40$
	4.8	75%	
	5.3	80%	
3	4	65%	$y = 10x + 40$
	4.5	70%	
	5	75%	
4	4	65%	$y = 10x + 40$
	4.5	70%	
	5	75%	
5	4.8	65%	$y = 8.3333x + 40$
	5.4	70%	
	6	75%	

y= efficiency of boiler (%), x = load (KPPM)

Table 3.4: Relationship for the boiler efficiency

In case of the stoves, they are bottled after every 45 minutes. Two stoves are considered here for modeling purposes. When the stoves are bottled, they do not consume any BFG and thus the available BFG for the boilers is more than the normal. This is accommodated in the model, as the stoves pulling the required BFG from the BFG

location and after every 45 minutes this pulling of BFG is set to zero, thus modeling as the stoves are being bottled. This bottling time is set to be three minutes.

For the overall model, the set limits such as the maximum and the minimum firing rates for boilers, the steam flow rates of turbines, the set points for the accumulator, low pressure header, high pressure header, etc. are input into the model through arrays. The arrays input their values from an Excel sheet (initializing, before running the model), thus changing these values is easy. The arrays and the input values for the variables are shown in Appendix III. A relationship was obtained between the steam flow and the power generated for the turbines and this is used for the electric generation. Similarly, a linear relationship was developed for the boilers which simulate their ramping up and down, and for the turbines which pull the required steam depending upon the error in the low pressure header. The calculations are as shown in Table 3.5 and 3.6.

From the Table 3.4 it can be seen that the boilers operate in sequence. This is done as boilers 101 and 102 are more efficient than the others. Thus, if the steam pressure in the high pressure header goes below 800 psig boilers 101, 102 will fire at full blast, while the #3 boiler will fire at the required level indicated by the relation.

Boiler		Pounds of steam in HP (1000 lbs)	Boiler steam generation (1000 lbs)	Relation
#101	Min	20	3.3	$y = -x + 23.333$
	Max	18	5.3	
#102	Min	18	3.3	$y = -x + 21.333$
	Max	16	5.3	
#3	Min	16	2.2	$y = -1.4167x + 24.833$
	Max	14	5	
#4	Min	14	2.2	$y = -1.4167x + 22$
	Max	12	5	
#5	Min	12	3.7	$y = -1.1667x + 17.667$
	Max	10	6	

y= Boiler Steam generation (1000 lbs), x = Steam in HP header (1000 lbs)

Table 3.5: Relationship for the boiler ramping

Turbine		Pounds of steam in LP/HP (1000 lbs)	Steam Flow rate (1000 lbs/min)	Relation
T6	Min	200	1.2	$y = -0.9167x + 184.5$
	Max	194	6.7	
T9	Min	205	1.2	$y = -1.7667x + 363.33$
	Max	200	10	
Desuperheater	Min	194	0	$y = -0.9514x + 184.58$
	Max	180	13.32	
T8	Min	20	0.4	$y = 2.2917x - 45.417$
	Max	22	5	

y= Steam Flow rate (1000 lbs/min), x = Steam in HP and LP header (1000 lbs)

Table 3.6: Relationship for the turbine steam flow rate

As in the case of boilers, turbine #9 is given preference over turbine #6. But turbine #6 always operates at its minimum level. For the turbine #8, as it acts as a pressure relief valve for high pressure header, steam pressure in high pressure header is considered while calculating the relationship.

In all cases, bounds are put on the minimum and the maximum values in the model code, thus keeping level with the maximum and the minimum level of firing rates for the boilers and the minimum and the maximum steam flow rate for the turbines.

For the model, one entity represents 1000 lbs per minute of steam flow rate. Thus as one entity moves from boiler to turbine; 1000 lbs of steam flows from the boiler to the turbine. This time increment is selected from the fact that as the number of entities in the model at any instance increase the model runs slower. As the final objective is integrating the system equipment to understand the process better and to analyze the system for operations management, running the model in minutes instead of seconds satisfies the objectives with faster running speed.

The model is run with some specific level of steam in the high pressure header, low pressure header and some low pressure steam in the accumulator. The boilers already are producing the minimum amount of steam they produce. The turbines are also operating at their lowest steam flow rate. This is done so as to stabilize the system quickly. If the model is run empty at the start, then time will be wasted to reach

equilibrium and it will run erratic until equilibrium is attained. So some set specified levels are fixed and set before the model starts, which helps it stabilize quickly.

The structure of the model via its graphical representation as it appears on the computer screen is shown in Appendix I. Also the color code for the variables is shown in the table AI in Appendix I. The list of variables and their initial values are shown in Appendix II.

Chapter 4

Model Execution

4.1 Model Assumptions

The following assumptions are made while designing and executing the simulation model.

1. The plant has many low pressure steam users. In the model, a single user is considered which is equivalent to the total steam consumed by all the users.
2. It is assumed that the users will consume a minimum amount of low pressure steam which is nearly equal to the total amount of steam produced by the boilers at their lowest firing rate.
3. The pressure in the high pressure header is maintained at 800 psig.
4. The volume of the high pressure header is assumed to be same as the accumulator volume. This is done because no data exists for the high pressure header volume, while we have an exact volume of the accumulator.
5. The pressure in the low pressure header is maintained at 200 psig.
6. As the low pressure header supplies low pressure steam throughout the plant the volume of the low pressure header is very high and cannot be determined. In the model the volume is assumed to be such that 200,000 lbs of steam in the header correspond to 200 psig steam pressure.
7. For modeling purposes only two stoves are considered which consume the same amount of blast furnace gas as all the stoves in the plant.

4.2 Model Validation

Data was collected from the plant on various variables. This data is plotted so as to obtain an idea about the process. The model is then run with the set input variables. The output generator collects the data for all the variables. This data is exported to an Excel sheet and then plotted. These graphs are compared with each other for validation purposes. Three variables are considered here, viz. the BOP steam flow, vented steam and the pressure in the low pressure header.

From the following graphs, Figure 4.1 to 4.4, it can be seen that the model closely represents the actual system. The dynamics of the system are very well reflected by the simulation model. Thus the model is now ready for conducting experiments and analyzing the results.

Figure 4.1: BOP and Venting (Data Exported from the software)

Figure 4.2: BOP and Venting (From the collected data)

Figure 4.3: LP Header Pressure (From the data exported from software)

Figure 4.4: LP Header Pressures (From the collected data)

4.3 Conducting Experiments with the simulation model

The simulation model was run with different inputs and the output was analyzed. Two cases are considered here; the time at which the stoves are bottled and running the system with less boilers.

4.3.1 Time for bottling of stoves

The hot air that is blown in the blast furnace is preheated in the stoves. The stove is said to be bottled when the brick work is heated to the required temperature and is now ready to go ‘on-blast’. In this case, the valves on the stoves are shut and thus no gas or air is passed through the stove. Thus during the bottling of the stoves, the blast furnace gas available for the boilers is more than normal availability. The simulation model is now run with the following data input –

1. The tank charging point is set at 200 psig and the venting pressure is assumed to be 600 psig.
2. The user demand was considered to be 828,000 lbs per hour.

3. All the five boilers are working.
4. The BFG arrival is considered to be constant at 235 Mcf/min or 20.7 MMBtus.
5. The stoves are bottled when the BOP is on-blow (the steam from the waste heat boiler is at its maximum).
6. The bottling time for the stoves is three minutes.

After the model is run the output generator collects the data and can be analyzed for decision making. The data obtained after running the simulation is plotted in Figure 4.5. It is observed that there is flaring during the time the stoves are bottled.

Figure 4.5: Flaring when stoves are bottled while BOP is on-blow

From the steam diagram and the logic flow chart, it can be seen that when the BOP steam is on-blow the pressure in the low pressure header increases and that puts the turbines down. As the turbines ramp down the pressure in the high pressure header increases, thus the boilers are also ramped down. In such a case, the boilers will start consuming less BFG as they ramp down and if the stoves are bottled during this time then there is an excess of BFG and that cannot be consumed, thus the BFG is flared.

From the data the model generated, the amount of BFG flared is 1.55 MMbtu in the one hour simulation run. Assuming that this is the amount that will fall short for the boilers in the long run, they will consume natural gas. The average cost of natural gas is about \$ 5.5 /MMbtu. Thus the company may experience \$8.55 per hour extra cost. If this is integrated over a years span, then considering 50 weeks of operation and 7 days a week the company incurs additional cost of \$ 71,820 annually.

The solution of this problem is to bottle the stoves when the BOP is off-blow. There is a 45 minutes gap before the stove is again bottled. Thus this operation can be performed before the BOP goes on-blow.

The model is now run again with the same input data but the bottling is done when the BOP is off-blow. After the model is run the output generator collects the data and it can be analyzed. The data obtained after running the simulation is plotted in Figure 4.6. It is observed that there is no flaring of BFG.

Figure 4.6: Flaring when stoves are bottled while BOP is off-blow

As seen from the Figure 4.6, the strategy of bottling the stoves when the BOP is off-blow works. Thus the energy is utilized completely and this will reduce the extra cost to the plant.

4.3.2 Shutting down of boilers

Consider the above case; all the five boilers are working and the stoves are bottled when the BOP is off-blow. From the data gathered by the output generator of the simulation model, we can find out the total amount of natural gas consumed. Assuming the natural gas cost to be \$ 5.5 / MMBtu the natural gas cost can also be plotted with the natural gas consumption. Figure 4.7 shows the natural gas consumption and the cost associated with it.

Figure 4.7: Natural gas consumption and cost

From the data generated by the model and the plot above, it can be seen that the average consumption of natural gas is about 10 MMbtu for the one hour run. The average cost of natural gas is then about \$55 per hour.

The user demand is constant and can be well satisfied by four boilers. Thus to check a new operating strategy, one of the five boilers is shut down. Say, boiler #4 is now shut down and the model is run. The input data remains the same but the only change is that we now run four boilers instead of five. The data is generated for the natural gas consumption and cost. Figure 4.8 shows a plot for the generated data.

Figure 4.8: Natural gas consumption and cost

From the graph it can be observed that the average consumption of natural gas is reduced from 10 MMbtu/hr to about 8 MMbtu/hr. Thus the cost of natural gas also reduces to about \$ 45 per hour. This is \$ 10 savings per hour by just shutting down one boiler. If this is integrated over one year span, then considering 50 weeks of operation and 7 days a week the company saves about \$ 84,000 annually. Due to shutting of one boiler, boilers #101, #102 and #3 are mostly run at full loads and the fourth boiler, boiler #5 is run at partial load. Also, a small pressure drop is observed in the high pressure

header. The pressure reduces from average 800 psig to 760 psig. But this pressure drop is not significant and can be tolerated by the system components.

4.4 Conclusion from above scenarios

The plant currently uses a combination of base loading and parallel ramping to regulate the high pressure header conditions. Thus, all the boilers “hunt” up and down almost continuously. This type of operation leads to inefficient boiler usage. As designed in the model, the boilers should ramp up and down in sequence. This will help to operate the boilers at their most efficient levels.

From the above experiments, it can be seen that through the operating strategy of timing the bottling of stoves as well as shutting down of one of the boilers, the company can save considerable amount money, nearly \$ 150,000 annually. This will also help to minimize energy loss, making the system energy efficient.

4.5 Reducing the amount of steam vented from the accumulator

Another scenario can be run for reducing the steam vented from the accumulator. From Figure 3.5 it is seen that, the steam production is cyclical and within a span of 22 minutes the steam production goes from zero to well above 1,200,000 lbs/hr and back to zero. The same cycle repeats itself after a span of about 23 minutes. Thus it is a 45 minute cycle. A strategy can be analyzed which may help in reducing the amount of steam vented. The boilers should be set in such a way that as the BOP steam sets in the boilers will ramp down by themselves. This is integrating the BOP steam production (waste heat boilers) to the other boilers.

To set up the model for running the above scenario, some modification is required in the operation code for the boilers. The model is run for one hour. In that hour from the BOP cycle it is seen that the BOP sets in after 13 minutes. A code needs to be added to the existing operation code for the boilers, which will set the steam generation variable (Boiler_var) for all the boilers, to minimum at the 13th minute. And at the end of the BOP, the 34th minute set the variables back to normal, so that they operate according to the steam pressure in the high pressure header.

After making the modification to the operation code and running the model, following things must be analyzed:

1. Amount of steam vented as compared to normal operation.
2. The pressure in the high and the low pressure header.
3. The working of the turbines.
4. Whether the user is properly satisfied with low pressure steam.

The analysis of the above scenario may result into saving on the amount of steam vented from the accumulator. As the steam production in waste heat boilers increases, the normal boilers will be put at their lowest. Thus less steam will be added by the turbines to the low pressure header because they will also ramp down to maintain the high pressure header pressure. This will help to consume more amount of steam from the accumulator because the required steam for the low pressure header will be provided by the accumulator. Due to this, the steam pressure in the accumulator will lower, reducing the amount of steam vented.

Chapter 5

Conclusion and Future work

5.1 Conclusion

The iron and steel making is a complex process. Large amount of energy is consumed in this process. The major sources of energy consumed are coal, natural gas and electricity. On-site electricity generation is carried out by most of the integrated steel industries. This contributes to 10% of the total electric use in the steel industry. Large amounts of by-product gases are also generated during the production. This is a free source of energy and must be used instantaneously. To capture this energy the steel industries have computerized control on system equipment. But still some energy is vented to atmosphere. This leads to buying of natural gas. The venting of free energy can be avoided by linking different equipments so that they anticipate the dynamic energy fluctuations and use real time data communication for decision-making.

A simulation model is developed to mimic existing situation. The goal of understanding the process and integrating the system equipments can be achieved by developing this model. Data is collected from appropriate sources and then analyzed. The simulation model is designed and is then validated. This model can be used to perform some first-level evaluations of different control strategies in making control and operating strategy decisions. Different scenarios are run by varying the inputs in the model and the effects of changes are analyzed.

As a result of this work it is learnt that developing an operating strategy that allows using the absolute minimum number of boilers necessary to supply the load is of paramount importance. The rewards are so compelling that they will easily justify some investment in demand side load management capability and research into optimization of boiler combinations and risk management.

Secondly, it is also learnt that simulation can be used as a tool for management of extremely complex systems of boilers, fuel supplies and steam users. This simulation model has tremendous value in generating “risk or reward” analyses.

Another use of the model would be analysis of various boiler staging and control schemes under realistic loading conditions. At present, the plant uses a combination of base

loading and parallel ramping to regulate high pressure header conditions. This leads the boilers to “hunt” up and down almost continuously and further to inefficient boiler performance. The model is designed to ramp up the boilers in sequence. This will lead to run the boilers at their most efficient level. Similar strategies can be analyzed by the simulation model.

Finally, the model is ideal for studying the effects of changes prior to implementation thus avoiding the risks of implementation. The model can also be used as a training simulator for improving the proficiency of boiler operators and other personnel associated with the power house. This gives an opportunity to train the operators to handle unusual or even emergency situations without disrupting normal operations.

5.2 Future work

This research work has covered the basic objective of performing some first-level evaluations of different control strategies and to evaluate the usefulness of the simulation model in making control and operating strategy decisions. Secondly, the simulation model can be used for analysis of various control schemes under realistic loading conditions. The model is ideal for studying the effects of a change, prior to implementation thus avoiding the risks of implementation. To further refine the model used for these simulations, a good deal of effort would be required to gather adequate input data so as to generate realistic scenarios. Following future work is suggested for this research –

1. Accurate data must be collected for the control algorithms of different equipment. Similarly, accurate data must be collected related to system capacities, for e.g. the exact volume of the high pressure header.
2. Instead of using one minute time interval as present, use one second time interval. This would help to analyze the dynamics of the equipment as their response times are in seconds. But to consider the second time interval again accurate data of system is necessary.
3. Analyzing various boiler staging and control schemes for the boiler operations under realistic loading conditions.

4. Allowing the header pressures to float over a wider range instead of maintaining a specific pressure.

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Appendix I

Figure A1.1: Screenshot of the model

Color	Variable
Blue	Blast furnace gas (BFG)
Light green	Natural gas (NG)
Black	Steam flow rate / Firing rate for boilers
Purple	Efficiency of the boilers
Yellow	KP of steam in HP or LP
Pink	Pressure of steam corresponding to KP of steam
Red	Electricity generated by the turbines
White	User requirement
Dark green	BOP cycle
Orange	Represents the loss of energy (BFG flaring and Steam venting)

Table A1.1: Color Coding Scheme

Appendix II
Table A2.1: List of variables

Sr. No	Variable	Type	Initial Value	Used For
1	User_req_counter	Real	0	User demand
2	User_cumm	Real	0	Cumulative user demand
3	Dummy_arrival_counter	Real	0	Arrival at user
4	HP_Steam_Arrival	Real	0	Arrival at High Pressure (HP) header
5	BOP_Steam_arrival	Real	1	Arrival at BOP
6	LP_Steam_arrival_var	Real	0	Arrival at Low Pressure (LP) header
7	Total_LP_steam	Real	0	Amount of steam in LP
8	desuperheater	Real	0	Steam flow through desuperheater
9	Boiler_var101	Real	3.33	Steam generation in boiler 101
10	Boiler_var101cumm	Real	0	Graph for the steam generation in 101
11	HP_Steam_var	Real	20	Amount of steam in HP header
12	turbo_blower	Real	0	Steam flow through Turbo blower
13	m1	Real	0	Steam in Waste heat boilers
14	bol	Real	0	Counter
15	Boiler_var102	Real	3.33	Steam generation in boiler 102
16	Boiler_var102cumm	Real	0	Graph for the steam generation in 102
17	Boiler_var3	Real	2.17	Steam generation in boiler 3
18	Boiler_var3cumm	Real	0	Graph for the steam generation in 3
19	Boiler_var4	Real	2.17	Steam generation in boiler 4
20	Boiler_var4cumm	Real	0	Graph for the steam generation in 4
21	Boiler_var5	Real	3.67	Steam generation in boiler 5
22	Boiler_var5cumm	Real	0	Graph for the steam generation in 5
23	NG_101	Real	0	Natural gas consumption for boiler 101
24	NG_102	Real	0	Natural gas consumption for boiler 102
25	NG_3	Real	0	Natural gas consumption for boiler 3
26	NG_4	Real	0	Natural gas consumption for boiler 4
27	NG_5	Real	0	Natural gas consumption for boiler 5
28	flaregraph	Real	0	Graph of the Flared BFG
29	Flare	Real	0	Flaring of BFG
30	MW30tur	Real	0	Power Generation in turbine #8
31	MW6tur	Real	0	Power Generation in turbine #6
32	MW9tur	Real	0	Power Generation in turbine #9
33	Total	Real	200	Amount of Steam in LP
34	m	Real	8	Amount of steam in accumulator
35	m2	Real	0	Steam Flow from accumulator to LP

36	LP_Pressure	Real	0	Pressure in LP
37	HP_Pressure	Real	0	Pressure in HP
38	NG_cumm	Real	0	Cummulative natural gas consumption
39	NG_tot	Real	0	Total natural gas consumption
40	Stove_var	Real	3.59	BFG consumed by stove 1
41	Stove_var2	Real	3.59	BFG consumed by stove 2
42	arr_value	Real	1	Pointer in array
43	i	Real	0	Counter
44	k	Real	0	Counter
45	Noise_var	Real	0	Noise for the user
46	Tot_BFGgraph	Real	0	Graph for total BFG consumed
47	Tot_BFG	Real	0	Total BFG consumed
48	btu101	Real	0	Fuel requirement for boiler 101 in terms of btu's
49	btu102	Real	0	Fuel requirement for boiler 102 in terms of btu's
50	btu3	Real	0	Fuel requirement for boiler 3 in terms of btu's
51	btu4	Real	0	Fuel requirement for boiler 4 in terms of btu's
52	btu5	Real	0	Fuel requirement for boiler 5 in terms of btu's
53	Totalbtu	Real	0	Total requirement of fuel for all boilers in terms of btu's
54	pi101	Real	0	Natural gas consumed by pilot for boiler 101
55	pi102	Real	0	Natural gas consumed by pilot for boiler 102
56	pi3	Real	0	Natural gas consumed by pilot for boiler 3
57	pi4	Real	0	Natural gas consumed by pilot for boiler 4
58	pi5	Real	0	Natural gas consumed by pilot for boiler 5
59	watervar	Real	0	For water addition in desuperheater
60	Vent_var	Real	0	Amount of steam vented
61	s1	Real	3.59	BFG consumed by Stove 1
62	s2	Real	3.59	BFG consumed by Stove 2
63	sc1	Integer	2	For timing of first stove's bottling (in terms of the minute it is bottled)

64	sc2	Integer	2	For timing of second stove's bottling (in terms of the minute it is bottled)
65	error	Real	0	Calculating the amonut of steam required in LP header
66	MW9	Real	5.58	Steam flow through turbine #9
67	MW9graph	Real	0	Graph of steam flow through turbine #9
68	MW6tur	Real	3.92	Steam flow through turbine #6
69	MW6graph	Real	0	Graph of steam flow through turbine #6
70	desuper	Real	6.67	Steam flow through desuperheater
71	desupergraph	Real	0	Graph of steam flow through desuperheater
72	count1	Real	0	Counter
73	tur30	Real	0	Graph of steam flow through turbine #8
74	MW30	Real	2.71	Steam flow through turbine #8
75	BOPgraphvar	Real	0	Graph of the BOP steam
76	bol1	Real	0	Counter
77	bol2	Real	0	Counter
78	bol3	Real	0	Counter
79	Total1	Real	0	Graph of amount of steam in LP
80	HP_Steam_var1	Real	0	Graph of amount of steam in HP
81	bol4	Integer	0	Counter
82	eff101	Real	0	Efficiency for boiler 101
83	eff102	Real	0	Efficiency for boiler 102
84	eff3	Real	0	Efficiency for boiler 3
85	eff4	Real	0	Efficiency for boiler 4
86	eff5	Real	0	Efficiency for boiler 5
87	bol5	Integer	0	Counter
88	bol6	Integer	0	Counter
89	bol7	Integer	0	Counter
90	bol8	Integer	0	Counter
91	bol9	Integer	0	Counter
92	bol10	Integer	0	Counter
93	bol11	Integer	0	Counter
94	mgraph	Real	0	Graph of amount of steam in accumulator
95	Ventgraph	Real	0	Graph of amount of steam vented
96	m2graph	Real	0	Graph of amount of steam flowing from accumulator to LP
97	count2	Integer	0	Counter

98	sv	Real	0	Specific Volume of steam in accumulator
99	tp	Real	0	Steam Pressure in accumulator
100	bfgcon101	Real	0	BFG consumed by boiler 101
101	bfgcon102	Real	0	BFG consumed by boiler 102
102	bfgcon3	Real	0	BFG consumed by boiler 3
103	bfgcon4	Real	0	BFG consumed by boiler 4
104	bfgcon5	Real	0	BFG consumed by boiler 5
105	bfgcontot	Real	0	Total BFG consumed
106	Ngcost	Real	0	Total natural gas cost
107	g1	Real	0	Counter

Appendix III

Input values / Arrays

Sr. No	Equipment No.		KPPM
1	101	Min	3.33
2		Max	5.33
3	102	Min	3.33
4		Max	5.33
5	3	Min	2.17
6		Max	5.00
7	4	Min	2.17
8		Max	5.00
9	5	Min	3.67
10		Max	6.00
11	T6	Min	1.17
12		Max	6.67
13	T9	Min	1.17
14		Max	10.00
15	T8	Min	0.42
16		Max	5.00
17	Ramp rates	101	0.02
18		102	0.02
19		3	0.01
20		4	0.01
21		5	0.01
22		T6	0.20
23		T9	0.20
24		T8	0.24
25	Desuper	Ramp rate	1.00
26		Min	0.00
27		Max	13.32
28	T6	Avg	3.92
29	T9	Avg	5.58
30	T8	Avg	2.71

Table A3.1: Array Name - arrboltur[] (Array for boilers, turbine and desuperheater data)

Sr. No	Set Points	Values in model	Unit
1	HP set pt	22	KP
2	LP set pt	17.5	KP
3	Vent set pt	30	KP
4	Tank to LP	4.8	KPPM
5	Tank set pt	8	KP
6	User	13.8	KPPM
7	TB	6.51	KPPM
8	Vent capacity	17.04	KP
9	Desuperheater	13.32	KPPM
10	rate of flow (tank to LP)	1	KPPM
11	rate of flow (tank to Vent)	1	KPPM
12	BFG arrival	20.72	MMBtu's
13	Stove arrival1	3.59	MMBtu's
14	Stove arrival2	3.59	MMBtu's
15	Pilotarrival101	0.33	MMBtu's
16	Pilotarrival102	0.33	MMBtu's
17	Pilotarrival3	0.42	MMBtu's
18	Pilotarrival4	0.42	MMBtu's
19	Pilotarrival5	0.87	MMBtu's
20	NGarrival101	1.00	MMBtu's
21	NGarrival102	1.00	MMBtu's
22	NGarrival3	1.25	MMBtu's
23	NGarrival4	1.25	MMBtu's
24	NGarrival5	2.60	MMBtu's

Table A3.2: Array Name - arrsetpt[] (Array for various set points and initial values)

Cummsec[]	boparr[]
Minute	Value (KP)
1	0.341
2	0.335
3	0.330
4	0.324
5	0.319
6	0.313
7	0.308
8	0.302
9	0.296
10	0.291
11	0.285
12	0.280
13	0.274
14	1.357
15	4.723
16	6.553
17	7.956
18	9.592
19	10.827
20	12.084
21	14.905
22	17.163
23	17.987
24	19.997
25	20.269
26	18.748
27	18.082
28	17.875
29	17.880
30	18.102

Cummsec[]	boparr[]
Minute	Value (KP)
31	17.089
32	9.715
33	2.759
34	0.791
35	0.479
36	0.477
37	0.475
38	0.473
39	0.471
40	0.469
41	0.466
42	0.464
43	0.462
44	0.460
45	0.458
46	0.456
47	0.454
48	0.452
49	0.450
50	0.448
51	0.446
52	0.444
53	0.442
54	0.440
55	0.438
56	0.436
57	0.433
58	0.431
59	0.429
60	0.427

Table A3.3: Array Name: Cummsec[] and boparr[] (Arrays for BOP arrivals, one is for the minute and other for the value)

Appendix IV

I] Relationship between volume of steam in accumulator and corresponding pressure

Figure A4.1: Graph of Pressure vs. Specific Volume

Using the saturated water – pressure table [27], for the range of pressure from 180 psig to 1000 psig, the specific volume of steam is found out at each level pressure level and is plot as shown in figure . An exponential relationship is obtained which is:

$$\text{Pressure (psig)} = 459 * (\text{Specific Volume})^{-0.09923}$$

As the volume of the tank is known, consists of two pipes 10 feet in diameter and 120 feet in length, we can calculate the amount of steam in tank at a given pressure or vice versa. Finally the relationship is as under:

$$\text{Pressure (psig)} = 459 * (18852 / (m * 1000))^{-0.09923}$$

where, m = amount of steam in tank in 1000 lbs.

II] Relationship between volume of steam in high pressure header and corresponding pressure

Figure A4.2: Graph of Specific Volume vs. Pressure

Using the superheated water table [27], for the range of pressure from 740 psig to 830 psig, the specific volume of steam is found out at each level pressure level and is plot as shown in figure . The linear relationship is obtained over the given range which is:

$$\text{Specific Volume} = -0.0012 * \text{Pressure} + 1.805$$

The volume of the high pressure header is assumed to be same as that of the tank (18852 cubic feet), we can calculate the amount of steam in the high pressure header at any given pressure or vice versa. Finally the relationship is as under:

$$\text{Pressure (psig)} = 1504.08 - (833.33 * (18852 / (m * 1000)))$$

where, m = amount of steam in high pressure header in 1000 lbs.

Appendix V

The following shows calculations performed in the operation code for the software. The numbers here are related to the logic flow chart in the previous section, as shown in Figure 3.8. Each number is related to a process block or a decision box in the logic flow process chart.

1. Initialize the variable for user (User_req_counter) to the user demand at that minute. This demand is addition of the normal demand plus the noise, if any noise is put into the model. The variable related to noise is Noise_var. thus,

$$\text{User demand} = \text{User_req_counter} + \text{Noise_var}$$

2. This user demand is then pulled from the low pressure header. Thus the amount of steam in the low pressure header (Total) will reduce.

$$\text{Total} = \text{Total} - \text{User_req_counter} - \text{Noise_var}$$

3. The pulling of steam from the low pressure header will reduce the pressure in the header. As per the assumption for the low pressure header, the 1000 lbs of steam correspond to 1 psig pressure. Thus the user pull will be the amount, which equals the reduction in steam pressure. The steam pressure should be maintained at 200 psig, thus here we check the steam pressure (Total) and depending on its value we either ramp down the turbines or pull steam from the accumulator.

4. If the steam pressure (Total) is less than 200 psig, we calculate the error. The variable is named as 'error' itself. This error is the amount of steam required to maintain the steam pressure at 200 psig. Thus

$$\text{error} = 200 - \text{Total}$$

If the error is less than zero it is set back to zero.

5. The accumulators are charged up to a point before they send steam to the low pressure header. This test box checks the steam level (m) in accumulator, also

called as Tank. If the steam is more than 8000 lbs (200 psig pressure) then the steam is routed to the low pressure header.

6. The next test box checks whether the steam in accumulator can satisfy the 'error'. If the error is greater than the available steam, all the steam is routed to the low pressure header ('Yes' for the test box). Again it checks the steam pressure and moves through the loop. In case, where no steam is available in the accumulator, the steam will be supplied by the turbines.
7. As the turbines ramp up new steam flow rate will be calculated with the updated amount of steam in the low pressure header (Total). Thus for the turbines –

$$MW9 = -1.7667 * \text{Total} + 363.33$$

$$MW6 = -0.9167 * \text{Total} + 184.5$$

For both the turbine variables the maximum and minimum bounds are checked. As this amount of steam is pulled by the turbines it is added to the low pressure header. Thus for the low pressure header –

$$\text{Total} = \text{Total} + MW9$$

$$\text{Total} = \text{Total} + MW6$$

This same amount is then reduced from the high pressure header. And thus for the high pressure header –

$$HP_Steam_var = HP_Steam_var - MW9$$

$$HP_Steam_var = HP_Steam_var - MW6$$

8. In case when the turbines are ramped down, again new steam flow rate is calculated using the same relations. But in this case due to the variable Total, which is greater than 200 will cause the steam flow rate to reduce (variables MW9 and MW6) and thus less steam is pulled from the high pressure header and added to the low pressure header. The pressure in the high pressure header is then checked for its set point.

9. When the 'error' is smaller than, the amount of steam in accumulator, only the required steam is routed to the low pressure header. This will increase the amount of steam in the accumulator.
10. In the accumulator we check for two levels of steam. First the charging point (CP), as stated earlier is 8000 lbs (200 psig). If the steam is less than the set point, then no steam is routed to the low pressure header and the steam is accumulated in the accumulator. As the accumulator is charged to the level of 8000 lbs (200 psig) steam is routed to low pressure header. The variable m2, is the amount of steam passed by the accumulator to the low pressure header.

$$m2 = (m - CP) * \text{Rate of transfer from accumulator to low pressure header}$$

This steam is then added to the low pressure header –

$$\text{Total} = \text{Total} + m2$$

11. The steam from the waste heat boilers, the BOP steam (BOP_Steam_arrival), is directly added to the accumulator. Secondly, if the amount of steam is greater than 30,000 lbs (600 psig), the venting point (VP), steam is vented. The vent has a maximum capacity of 17,040 lbs/min, which is checked while venting the steam. Thus from the above description the amount of steam to be vented is –

$$\text{Vent_var} = (800/(200*60))*(tp-600),$$

where, tp is the pressure in the accumulator based on the amount of steam present. The pressure is calculated by finding the specific volume (sv) of the steam in the accumulator. The expressions for the steam specific volume and pressure are as given below –

$$sv = (18852/(m*1000))$$

$$tp = 459*(sv)^{-0.9923}$$

The amount of steam in accumulator (m) is given by –

$$m = m + \text{BOP_Steam_arrival} - m2 - \text{Vent_var}$$

12. When the turbines cannot suffice the need of steam in the low pressure header the desuperheaters are used along with the turbines. The steam flow rate for the turbines are calculated as specified earlier. For the desuperheaters, the steam flow rate is given by –

$$\text{desuper} = -0.9514 * \text{Total} + 184.58$$

Similar to that of the turbines, desuperheaters will pull the required amount from the high pressure header and add it to the low pressure header. Thus the calculations of desuperheaters operation are similar to that of the turbines mentioned above.

$$\text{HP_Steam_var} = \text{HP_Steam_var} - \text{desuper}$$

$$\text{Total} = \text{Total} + \text{desuper}$$

13. As the turbines and the desuperheaters pull the steam from the high pressure header, the steam in the high pressure header reduces. Thus the pressure in the high pressure header reduces. We calculate the steam pressure in the high pressure header with the following expression –

$$\text{HP_Pressure} = 1504.08 - (833.33 * (18852 / (\text{HP_Steam_var} * 1000)))$$

14. The pressure in the high pressure header is maintained at 800 psig. If the pressure is more than 800 psig, the turbine # 8 is ramped up pulling the excess steam from the header. This ramping up the turbine is similar to the one explained earlier. The steam flow rate for the turbine (MW30) is calculated by the expression –

$$\text{MW30} = 2.2917 * \text{HP_Steam_var} - 45.417$$

As this steam is pulled from the high pressure header, the steam in the high pressure header reduces. Thus

$$\text{HP_Steam_var} = \text{HP_Steam_var} - \text{MW30}$$

15. Along with ramping of turbine, the boilers are ramped down so as to minimize the amount of steam put in the high pressure header. With the HP_Steam_var variable, the firing rates of the boilers are calculated for each of the boiler the firing rates are calculated as follows –

$$\begin{aligned}\text{Boiler_var101} &= -\text{HP_Steam_var} + 23.33 \\ \text{Boiler_var102} &= -\text{HP_Steam_var} + 21.33 \\ \text{Boiler_var3} &= -1.42 * \text{HP_Steam_var} + 24.83 \\ \text{Boiler_var4} &= -1.42 * \text{HP_Steam_var} + 22 \\ \text{Boiler_var5} &= -1.17 * \text{HP_Steam_var} + 17.667\end{aligned}$$

For all the boiler variables the maximum and minimum bounds are checked.

16. In case when the pressure in the high pressure header is less than 800 psig, the boilers are ramped up so that they input more steam. As in the above case, new firing rates of the boilers are calculated using the same expressions. But in this case due to the variable HP_Steam_var, which is less than 800 will cause the firing rates to increase.

17. As we calculate the new firing rate for the boilers, the fuel requirement for each is also calculated by expressions –

$$\begin{aligned}\text{btu101} &= (\text{Boiler_var} / (\text{eff101}/100)) - \text{pi101} \\ \text{btu102} &= (\text{Boiler_var} / (\text{eff102}/100)) - \text{pi102} \\ \text{btu3} &= (\text{Boiler_var} / (\text{eff3}/100)) - \text{pi3} \\ \text{btu4} &= (\text{Boiler_var} / (\text{eff4}/100)) - \text{pi4} \\ \text{btu5} &= (\text{Boiler_var} / (\text{eff5}/100)) - \text{pi5}\end{aligned}$$

where,

all pi's are the fuel required by the boiler's pilots and all eff's are the efficiency of boilers given by the expressions –

$$\begin{aligned}\text{eff101} &= 9.375 * \text{Boiler_var101} + 40 \\ \text{eff102} &= 9.375 * \text{Boiler_var102} + 40 \\ \text{eff3} &= 10 * \text{Boiler_var3} + 40\end{aligned}$$

$$\text{eff4} = 10 * \text{Boiler_var4} + 40$$

$$\text{eff5} = 8.33 * \text{Boiler_var5} + 40$$

Total amount of btu's (Totalbtu) are calculated and then compared with the available BFG (Tot_BFG). The total fuel required is as per expression –

$$\text{Totalbtu} = \text{btu101} + \text{btu102} + \text{btu3} + \text{btu4} + \text{btu5}$$

18. Each boiler will check if the BFG can suffice its fuel need. If it can, then that quantity of fuel is then absorbed from the Tot_BFG. Thus taking the case for boiler 101, if the available BFG is sufficient to keep the boiler at required firing level then,

$$\text{Tot_BFG} = \text{Tot_BFG} - \text{btu101}$$

In case where the available BFG cannot satisfy the fuel requirement completely, the boiler will consume the available BFG and then for the remaining requirement, natural gas is used. Thus in case where boiler 101 requires more fuel than available BFG following calculations are performed –

$$\text{btu101} = \text{btu101} - \text{Tot_BFG} \text{ (Uses the available BFG)}$$

$$\text{NG_101} = \text{btu101} \text{ (the remaining needs is sufficed by natural gas)}$$

19. Here NG_101 is the variable which indicates the quantity of natural gas is consumed by boiler 101. The same calculations are performed by all the boilers. We can now calculate the Total amount of natural (NG_tot) gas consumed by the expression –

$$\text{NG_tot} = \text{NG_101} + \text{NG_102} + \text{NG_3} + \text{NG_4} + \text{NG_5} + \text{pi101} + \text{pi102} + \text{pi3} + \text{pi4} + \text{pi5}$$

And the natural gas cost can be calculated as –

$$\text{NG_cost} = \text{NG_tot} * 5.5$$

20. In case where the amount of BFG is more than consumed by the stoves and the boilers, the BFG is flared. This amount is vented to the atmosphere and thus lost. Thus to keep a track of it –

$$\text{Tot_BFG} = \text{Tot_BFG} - \text{flare}$$

Where ‘flare’ is the variable denoting the quantity of BFG flared.

21. The process initializes the variables (s1, s2) related to the stoves. These represent the amount of BFG consumed by the stoves. When the stoves are bottled then they do not consume any BFG, thus the variables are set to zero if the stoves are bottled at a particular minute and after the bottling time, it is again set back to its original value.

Table A5.1: Table of energy related variables

Sr No.	Variable	Aspect or Function	Units	Range
1	User_req_counter	User Demand	1000 lbs/min	13.8
2	Noise_var	Noise for User	1000 lbs/min	±10% of User Demand
3	Total	Steam in low pressure header in 1000 lbs	1000 lbs	180 - 200
4	error	Low pressure header	1000 lbs	0 - 20
5	m	Steam in Tank or Accumulator in 1000 lbs	1000 lbs	8 - 30
6	MW9	Steam flow rate of Turbine 9	1000 lbs/min	1.2 - 10
7	MW6	Steam flow rate of Turbine 6	1000 lbs/min	1.2 - 6.7
8	HP_Steam_var	Steam in High pressure header in 1000 lbs	1000 lbs	10 - 22
9	m2	Rate of flow from accumulator to low pressure header	1000 lbs/min	0 - 4.8
10	Vent_var	Steam vented in 1000 lbs/min	1000 lbs/min	0 - 17.04
11	tp	Steam pressure in accumulator	psig	200 - 1000
12	BOP_Steam_arrival	BOP	1000 lbs/min	0 - 20
13	desuper	Steam flow rate of Desuperheater	1000 lbs/min	0 - 13.32
14	HP_Pressure	Pressure in high pressure header	psig	740 - 830
15	MW30	Steam flow rate of Turbine 8	1000 lbs/min	0.4 - 5
16	Boiler_var101	1000 lbs of Steam generated by Boiler 101	1000 lbs/min	3.3 - 5.3
17	Boiler_var102	1000 lbs of Steam generated by Boiler 102	1000 lbs/min	3.3 - 5.3
18	Boiler_var3	1000 lbs of Steam generated by Boiler 3	1000 lbs/min	2.2 - 5
19	Boiler_var4	1000 lbs of Steam generated by Boiler 4	1000 lbs/min	2.2 - 5

20	Boiler_var5	1000 lbs of Steam generated by Boiler 5	1000 lbs/min	3.7 - 6
21	btu101	Fuel requirement of Boiler 101	MMbtu	3.8 - 6.3
22	btu102	Fuel requirement of Boiler 102	MMbtu	3.8 - 6.3
23	btu3	Fuel requirement of Boiler 3	MMbtu	2.3 - 5.8
24	btu4	Fuel requirement of Boiler 4	MMbtu	2.3 - 5.8
25	btu5	Fuel requirement of Boiler 5	MMbtu	3.7 - 6.6
26	eff101	Efficiency of Boiler 101	%	65 - 80
27	eff102	Efficiency of Boiler 102	%	65 - 80
28	eff3	Efficiency of Boiler 3	%	65 - 75
29	eff4	Efficiency of Boiler 4	%	65 - 75
30	eff5	Efficiency of Boiler 5	%	65 - 75
31	pi101	Pilot for Boiler 101	MMbtu	0.33
32	pi102	Pilot for Boiler 102	MMbtu	0.33
33	pi3	Pilot for Boiler 3	MMbtu	0.42
34	pi4	Pilot for Boiler 4	MMbtu	0.42
35	pi5	Pilot for Boiler 5	MMbtu	0.87
36	Totalbtu	Total fuel requirement	MMbtu	33.33 - 18.33
37	Tot_BFG	Total amount of BFG produced per min	MMbtu	20.71
38	NG_101	Natural gas consumed by Boiler 101	MMbtu	0 - 6.3
39	NG_102	Natural gas consumed by Boiler 102	MMbtu	0 - 6.3
40	NG_3	Natural gas consumed by Boiler 3	MMbtu	0 - 5.8
41	NG_4	Natural gas consumed by Boiler 4	MMbtu	0 - 5.8
42	NG_5	Natural gas consumed by Boiler 5	MMbtu	0 - 6.6
43	NG_tot	Total amount of Natural gas consumed	MMbtu	0 - 30.8
44	NG_cost	Total Natrual gas cost	\$	0 - 169.4
45	flare	Amount of BFG flared	1000 lbs/min	-
46	s1	Amonut of BFG consumed by stove 1	MMbtu	3.58
47	s2	Amonut of BFG consumed by stove 2	MMbtu	3.58

Appendix VI

Source Code

Name	Locations		Stats	Rules
	Cap	Units		
Boiler101	inf	1	Time Series	Oldest
HP_Steam	inf	1	Time Series	Oldest
BP_Turbine6	inf	1	Time Series	Oldest
BP_Turbine9	inf	1	Time Series	Oldest
Turbine_30MW	inf	1	Time Series	Oldest
De_Sup_Heater	inf	1	Time Series	Oldest
LP	inf	1	Time Series	Oldest
User	inf	1	Time Series	Oldest
Vent	inf	1	Time Series	Oldest
BOP	inf	1	Time Series	Oldest
Dummy_LP_User	inf	1	Time Series	Oldest
Dummy_BP6	inf	1	Time Series	Oldest
Dummy_BP9	inf	1	Time Series	Oldest
Dummy_Desup_LP	inf	1	Time Series	Oldest
Turboblower	inf	1	Time Series	Oldest
Waste_heat_boiler	inf	1	Time Series	Oldest
Dummy_turbo	inf	1	Time Series	Oldest
Boiler102	inf	1	Time Series	Oldest
Boiler3	inf	1	Time Series	Oldest
Boiler4	inf	1	Time Series	Oldest
Boiler5	inf	1	Time Series	Oldest
BFG	inf	1	Time Series	Oldest
NG101	inf	1	Time Series	Oldest
DummyNG102	inf	1	Time Series	Oldest
DummyNG101	inf	1	Time Series	Oldest
DummyNG3	inf	1	Time Series	Oldest
DummyNG4	inf	1	Time Series	Oldest
DummyNG5	inf	1	Time Series	Oldest
NG102	inf	1	Time Series	Oldest
NG3	inf	1	Time Series	Oldest
NG4	inf	1	Time Series	Oldest
NG5	inf	1	Time Series	Oldest
Combustion	inf	1	Time Series	Oldest
BFG_flaring	inf	1	Time Series	Oldest
DummyBFG	inf	1	Time Series	Oldest
Tank	inf	1	Time Series	Oldest
Stove	inf	1	Time Series	Oldest
Dummystove	inf	1	Time Series	Oldest
Stove2	inf	1	Time Series	Oldest
Dummystove2	inf	1	Time Series	Oldest
Noise	inf	1	Time Series	Oldest
Pilot101	inf	1	Time Series	Oldest
Pilot102	inf	1	Time Series	Oldest
Pilot3	inf	1	Time Series	Oldest
Pilot4	inf	1	Time Series	Oldest
Pilot5	inf	1	Time Series	Oldest

Entities		
Name	Speed (fpm)	Stats
User_requirement	1550	Time Series
LP_Steam_arrival	1550	Time Series
High_Press_Steam	1550	Time Series
BOP_Steam	1550	Time Series
LP_steam	1550	Time Series
Vent_Arrival	1550	Time Series
turbo_ent	1550	Time Series
NG_boiler101	1550	Time Series
NG_boiler102	1550	Time Series
NG_boiler3	1550	Time Series
NG_boiler4	1550	Time Series
NG_ent101	1550	Time Series
NG_boiler5	1550	Time Series
BFG_ent	1550	Time Series
NG_ent102	1550	Time Series
NG_ent3	1550	Time Series
NG_ent4	1550	Time Series
NG_ent5	1550	Time Series
BFGflare	1550	Time Series
Stove_arrival	1550	Time Series
Stove_arrival2	1550	Time Series
Noise_ent	1550	Time Series
Pilotent101	1550	Time Series
Pilotent102	1550	Time Series
Pilotent3	1550	Time Series
Pilotent4	1550	Time Series
Pilotent5	1550	Time Series
Water	1550	Time Series
Anci	1550	Time Series

Path Networks							
Name	Type	T/S	From	To	BI	Dist/Time	Speed Factor
LP_User_Network	Passing	Speed & Distance	N1	N2	Bi	1	1
			N2	N3	Bi	1	1
			N2	N4	Bi	1	1
Boiler_LP_Network	Passing	Speed & Distance	N1	N2	Bi	1	1
			N2	N3	Bi	1	1
			N2	N5	Bi	1	1
			N5	N7	Bi	1	1
			N7	N8	Bi	1	1
			N3	N6	Bi	1	1
			N6	N8	Bi	1	1
			N9	N2	Bi	1	1
			N10	N2	Bi	1	1
			N11	N2	Bi	1	1
			N12	N2	Bi	1	1
			N2	N4	Bi	1	1
turbo_network	Passing	Speed & Distance	N4	N13	Bi	1	1
			N13	N8	Bi	1	1
			N1	N2	Bi	1	1
			N2	N3	Bi	1	1
			N1	N4	Bi	1	1

BFG_path	Passing	Speed & Distance	N1	N2	Bi	1	1
			N1	N3	Bi	1	1
			N1	N4	Bi	1	1
			N1	N5	Bi	1	1
			N1	N6	Bi	1	1
NG_path	Passing	Speed & Distance	N1	N7	Bi	1	1
			N4	N5	Bi	1	1
			N5	N6	Bi	1	1
			N7	N8	Bi	1	1
			N8	N9	Bi	1	1
			N10	N11	Bi	1	1
			N11	N12	Bi	1	1
			N13	N14	Bi	1	1
			N14	N15	Bi	1	1
			N5	N1	Bi	1	1
NG_path102	Passing	Speed & Distance	N8	N2	Bi	1	1
			N11	N3	Bi	1	1
			N14	N16	Bi	1	1
			N1	N2	Bi	1	1
			N2	N3	Bi	1	1
combustion_path	Passing	Speed & Distance	N2	N4	Bi	1	1
			N1	N2	Bi	1	1
BOP_network	Passing	Speed & Distance	N3	N2	Bi	1	1
			N2	N3	Bi	1	1
			N3	N4	Bi	1	1
			N3	N5	Bi	1	1
Stove_path	Passing	Speed & Distance	N1	N2	Bi	1	1
			N2	N3	Bi	1	1
			N1	N4	Bi	1	1
			N4	N5	Bi	1	1

Interfaces		
Net	Node	Location
LP_User_Network	N1	LP
	N2	Dummy_LP_User
	N3	User
	N4	Noise
Boiler_LP_Network	N1	Boiler101
	N2	HP_Steam
	N3	BP_Turbine6
	N5	De_Sup_Heater
	N6	Dummy_BP6
	N7	Dummy_Desup_LP
	N8	LP
	N9	Boiler102
	N10	Boiler3
	N11	Boiler4
	N12	Boiler5
	N4	BP_Turbine9
turbo_network	N13	Dummy_BP9
	N1	HP_Steam
	N2	Dummy_turbo
	N3	Turboblower
BFG_path	N4	Turbine_30MW
	N2	Boiler102

	N1	BFG
	N3	Boiler101
	N4	Boiler3
	N5	Boiler4
	N6	Boiler5
NG_path	N7	BFG_flaring
	N4	NG101
	N5	DummyNG101
	N6	Boiler101
	N7	NG3
	N8	DummyNG3
	N9	Boiler3
	N10	NG4
	N11	DummyNG4
	N12	Boiler4
	N13	NG5
	N14	DummyNG5
	N15	Boiler5
	N1	Pilot101
	N2	Pilot3
	N3	Pilot4
NG_path102	N16	Pilot5
	N1	NG102
	N2	DummyNG102
	N3	Boiler102
combustion_path	N4	Pilot102
	N3	BFG
	N2	Combustion
BOP_network	N1	Turboblower
	N1	BOP
	N2	Waste_heat_boiler
	N3	Tank
	N4	LP
	N5	Vent
Stove_path	N1	BFG
	N2	Dummystove
	N3	Stove
	N4	Dummystove2
	N5	Stove2

Entity	Location	Process	Routing			
		Operation	Blk	Output	Destination	Rule Move Logic
User_requirement	User	/*for BOP arrival*/				
		i=clock(min)				
		if k=0 then				
		{				
		arr_value=arr_value+1				
		k=Cummsec[arr_value]				
		}				
		if i=k then				
		{				
		BOP_Steam_arrival=boparr[arr_value]				
		BOPgraphvar = BOP_Steam_arrival				
		arr_value=arr_value+1				

```

        k=Cummsec[arr_value]
    }
    if bol=clock(min) then
    {
        bol=bol+1

/* Pilots */

        pi101 = arrsetpt[15]
        pi102 = arrsetpt[16]
        pi3 = arrsetpt[17]
        pi4 = arrsetpt[18]
        pi5 = arrsetpt[19]

/* HP side */

/*#8 Turbine*/
        MW30 = 2.2917*HP_Steam_var - 45.417
        if MW30 < arrboltur[15] then
        {
            MW30=arrboltur[15]
        }
        if MW30 > arrboltur[16] then
        {
            MW30 = arrboltur[16]
        }

/*Boiler's Steam generation*/
/*Boiler are ramped up in sequences depending upon their efficiencies*/

        Boiler_var101 = -HP_Steam_var + 23.333
        if Boiler_var101 >= arrboltur[2] then
        {
            Boiler_var101=arrboltur[2]
        }

        if Boiler_var101 <= arrboltur[1] then
        {
            Boiler_var101=arrboltur[1]
        }

        Boiler_var102 = -HP_Steam_var + 21.333
        if Boiler_var102 >= arrboltur[4] then
        {
            Boiler_var102=arrboltur[4]
        }

        if Boiler_var102 <= arrboltur[3] then
        {
            Boiler_var102=arrboltur[3]
        }

        Boiler_var5 = -1.1667*HP_Steam_var + 17.667
        if Boiler_var5 >= arrboltur[10] then
        {
            Boiler_var5=arrboltur[10]
        }

        if Boiler_var5 <= arrboltur[9] then
        {
            Boiler_var5=arrboltur[9]
        }

        Boiler_var3 = -1.4167*HP_Steam_var + 24.833
        if Boiler_var3 >= arrboltur[6] then
        {

```

```

        Boiler_var3=arrboltur[6]
    }

    if Boiler_var3 <= arrboltur[5] then
    {
        Boiler_var3=arrboltur[5]
    }

    Boiler_var4 = -1.4167*HP_Steam_var + 22
    if Boiler_var4 >= arrboltur[8] then
    {
        Boiler_var4=arrboltur[8]
    }

    if Boiler_var4 <= arrboltur[7] then
    {
        Boiler_var4=arrboltur[7]
    }

/*Variable for plotting of Steam generation */
Boiler_var101cumm=Boiler_var101
Boiler_var102cumm=Boiler_var102
Boiler_var3cumm=Boiler_var3
Boiler_var4cumm=Boiler_var4
Boiler_var5cumm=Boiler_var5

/*Efficiency of the Boilers*/
eff101 = 9.375*Boiler_var101+40
eff102 = 9.375*Boiler_var102+40
eff5 = 8.33*Boiler_var5+40
eff3 = 10*Boiler_var3+40
eff4 = 10*Boiler_var4+40

/*The Fuel required for the Boiler in terms of btu's*/
btu101 = (Boiler_var101 / (eff101/100))-arrsetpt[15]
btu102 = (Boiler_var102 / (eff102/100))-arrsetpt[16]
btu3 = (Boiler_var3 / (eff3/100))-arrsetpt[17]
btu4 = (Boiler_var4 / (eff4/100))-arrsetpt[18]
btu5 = (Boiler_var5 / (eff5/100))-arrsetpt[19]
Totalbtu=btu101+btu102+btu3+btu4+btu5

/*rate of flow from tank to LP header*/
m2=(m-arrsetpt[5])*arrsetpt[10]
if m2<0 then
{
    m2=0
}
if m2 > arrsetpt[4] then
{
    m2 = arrsetpt[4]
}
m2graph=m2

/*User req*/
User_req_counter = User_req_counter+arrsetpt[6]
User_cumm=User_req_counter
Total=Total-arrsetpt[6]
User_req_counter = User_req_counter-arrsetpt[6]
SEND arrsetpt[6] LP_steam TO Dummy_LP_User
Join arrsetpt[6] LP_steam

/*Noise for the User requirement*/
/*if Noise_var < 1.2 then
{
    Noise_var = Noise_var+0.2
}

if Noise_var > 1.1 then
{
    Noise_var = 0

```



```

    }

    Total=Total-Noise_var
    SEND 1 LP_steam TO Dummy_LP_User
    Join 1 LP_steam*/

/*LP side */

/*#9 turbine Steam Flow rate calculation*/
MW9 = -1.7667*Total + 363.33
if MW9 < arrboltur[13] then
{
    MW9=arrboltur[13]
}
if MW9 > arrboltur[14] then
{
    MW9 = arrboltur[14]
}
MW9graph = MW9
/*#6 turbine Steam Flow rate calculation*/
MW6=-0.9167*Total + 184.5
if MW6 < arrboltur[11] then
{
    MW6=arrboltur[11]
}
if MW6 > arrboltur[12] then
{
    MW6 = arrboltur[12]
}
MW6graph = MW6
/*Calculating the required steam to keep LP header pressure at 200psig*/
error = arrsetpt[2] - Total
/*Deuperheater used only if the turbines are insufficient to supply the steam*/
if error > (MW6+MW9) then
{
    /*
    Steam Flow rate calculation*/
    desuper=-0.9514*Total + 184.58
    if desuper < arrboltur[26] then
    {
        desuper=arrboltur[26]
    }
    if desuper > arrboltur[27] then
    {
        desuper = arrboltur[27]
    }
    desupergraph = desuper
    }
}

/*for the stoves*/
/*To set the time at which the stoves bottle*/
/*Can change by changing the value of sc1 and sc2*/
if i= sc1 then
{
    s1=0
}
if i=(sc1+2) then
{
    s1=arrsetpt[13]
    sc1=i+45
}
if i= sc2 then
{
    s2=0
}
if i=(sc2+2) then
{
    s2=arrsetpt[14]
}

```

```

        sc2=i+45
    }

1 User_requirement EXIT      FIRST 1 MOVE ON LP_User_Network

LP_Steam_arrival LP      /*Operation of #9 turbine*/
    if bol1 =clock(min) then
    {
        bol1=bol1+1
        LP_Steam_arrival_var = LP_Steam_arrival_var+1
        HP_Steam_var = HP_Steam_var - MW9
        Total = Total+MW9
        Total_LP_Steam=Total_LP_Steam+MW9
        /*for MW generated*/
        MW9tur=0.0785*(MW9**1.0753)
        SEND MW9 High_Press_Steam TO BP_Turbine9
        Join MW9 LP_steam
    }

/*Operation of #6 turbine*/
    if bol2 =clock(min) then
    {
        bol2=bol2+1
        HP_Steam_var = HP_Steam_var - MW6
        Total = Total+MW6
        Total_LP_Steam=Total_LP_Steam+MW6
        /*for MW generated*/
        MW6tur=0.1599*(MW6**0.9253)
        SEND MW6 High_Press_Steam TO BP_Turbine6
        Join MW6 LP_steam
    }

/*Operation of Desuperheater*/
    if bol3 =clock(min) then
    {
        bol3=bol3+1
        if error > (MW6+MW9) then
        {
            HP_Steam_var = HP_Steam_var - desuper
            Total = Total+desuper
            Total_LP_Steam=Total_LP_Steam+desuper
            desuperheater=desuperheater+desuper
            SEND desuper High_Press_Steam TO De_Sup_Heater
            Join desuper LP_steam
        }
    }
}

1* LP_Steam_arrival EXIT      FIRST 1 MOVE ON LP_User_Network

2 LP_steam      Dummy_LP_User      SEND 1 MOVE ON LP_User_Network

BFG_ent      BFG      /*Logic for flaring of BFG*/
/*If the BFG is not utilised completely it is Flared*/

    if bol10 = clock(min) then
    {
        bol10=bol10+1
        Tot_BFG = Tot_BFG + arrsetpt[12]-s1-s2
        if Tot_BFG > 0 then
        {
            Flare=Tot_BFG-btu101-btu102-btu3-btu4-btu5
            if Flare < 0 then
            {
                flaregraph = 0
            }
        }
    }

```

```

        }
        if Flare > 0 then
        {
            flaregraph = Flare
            Tot_BFG = Tot_BFG - Flare
            SEND Flare BFG_ent TO BFG_flaring
            /*Display "Flaring:" $flaregraph*/
        }
    }
    else
    {
        Flare = 0
    }
}
1 BFG_ent Dummystove,100 SEND 1 MOVE ON Stove_path

BFG_ent Dummystove2,100 SEND MOVE ON Stove_path
BFG_ent Combustion SEND MOVE ON combustion_path

BFG_ent Boiler101 ALT MOVE ON BFG_path
BFG_ent Boiler102 ALT MOVE ON BFG_path
BFG_ent Boiler3 ALT MOVE ON BFG_path
BFG_ent Boiler4 ALT MOVE ON BFG_path
BFG_ent Boiler5 ALT MOVE ON BFG_path
BFG_ent BFG_flaring ALT MOVE ON BFG_path

BFG_ent Dummystove 1 BFG_ent Stove JOIN 1 MOVE ON Stove_path

BFG_ent Dummystove2 1 BFG_ent Stove2 JOIN 1 MOVE ON Stove_path

Stove_arrival Stove /*Operation of Stove 1*/
SEND s1 BFG_ent TO Dummystove
Join s1 BFG_ent
Stove_var=s1
1 Stove_arrival EXIT FIRST 1 MOVE ON Stove_path

Stove_arrival2 Stove2 /*Operation of Stove 2*/
SEND s2 BFG_ent TO Dummystove2
Join s2 BFG_ent
Stove_var2 = s2

1 Stove_arrival2 EXIT FIRST 1 MOVE ON Stove_path

High_Press_Steam Boiler101 /*Logic for Boiler 101 pulling the required fuel*/
/*It will pull the BFG until its over and the remaining is satisfied by NG*/
if bol5 = clock(min) then
{
    bol5=bol5+1

    if Tot_BFG >= btu101 then
    {
        Tot_BFG = Tot_BFG - btu101
        SEND btu101 BFG_ent TO Boiler101
        bfgcon101 = btu101
        btu101 = 0
    }
    if Tot_BFG < btu101 then
    {
        if Tot_BFG < 0 then
        {
            NG_101 = btu101
            /*NG_tot = NG_101+NG_102+NG_3+NG_4+NG_5*/
            SEND btu101 NG_boiler101 TO Boiler101
        }
    }
}

```

```

        else
        {
            btu101 = btu101 - Tot_BFG
            SEND Tot_BFG BFG_ent TO Boiler101
            bfgcon101 = Tot_BFG
            Tot_BFG = 0
            NG_101 = btu101
            /*NG_tot = NG_101+NG_102+NG_3+NG_4+NG_5*/
            SEND btu101 NG_boiler101 TO Boiler101
        }
    }
    else
    {
        NG_101 = 0
    }
}

1 High_Press_Steam HP_Steam    FIRST 1 MOVE ON Boiler_LP_Network

High_Press_Steam Boiler102    /*Logic for Boiler 102 pulling the required fuel*/
/*It will pull the BFG until its over and the remaining is satisfied by NG*/
if bol6 = clock(min) then
{
    bol6=bol6+1
    if Tot_BFG >= btu102 then
    {
        Tot_BFG = Tot_BFG - btu102
        SEND btu102 BFG_ent TO Boiler102
        bfgcon102 = btu102
        btu102=0
    }
    if Tot_BFG < btu102 then
    {
        if Tot_BFG < 0 then
        {
            NG_102 = btu102
            SEND btu102 NG_boiler102 TO Boiler102
        }
        else
        {
            btu102 = btu102 - Tot_BFG
            SEND Tot_BFG BFG_ent TO Boiler102
            bfgcon102 = Tot_BFG
            Tot_BFG = 0
            NG_102 = btu102
            SEND btu102 NG_boiler102 TO Boiler102
        }
    }
    else
    {
        NG_102 = 0
    }
}

1 High_Press_Steam HP_Steam    FIRST 1 MOVE ON Boiler_LP_Network

High_Press_Steam Boiler3    /*Logic for Boiler 3 pulling the required fuel*/
/*It will pull the BFG until its over and the remaining is satisfied by NG*/
if bol7 = clock(min) then
{
    bol7=bol7+1
    if Tot_BFG >= btu3 then
    {
        Tot_BFG = Tot_BFG - btu3
        SEND btu3 BFG_ent TO Boiler3
        bfgcon3 = btu3
        btu3=0
    }
    if Tot_BFG < btu3 then
    {
        if Tot_BFG<0 then

```

```

        {
            NG_3 = btu3
            SEND btu3 NG_boiler3 TO Boiler3
        }
    else
    {
        btu3=btu3-Tot_BFG
        SEND Tot_BFG BFG_ent TO Boiler3
        bfgcon3 = Tot_BFG
        Tot_BFG = 0
        NG_3 = btu3
        SEND btu3 NG_boiler3 TO Boiler3
    }
}
else
{
    NG_3 = 0
}
}
1 High_Press_Steam HP_Steam    FIRST 1 MOVE ON Boiler_LP_Network

High_Press_Steam Boiler4    /*Logic for Boiler 4 pulling the required fuel*/
/*It will pull the BFG until its over and the remaining is satisfied by NG*/
if bol8 = clock(min) then
{
    bol8=bol8+1
    if Tot_BFG >=btu4 then
    {
        Tot_BFG = Tot_BFG - btu4
        SEND btu4 BFG_ent TO Boiler4
        bfgcon4 = btu4
        btu4=0
    }
    if Tot_BFG < btu4 then
    {
        if Tot_BFG < 0 then
        {
            NG_4 = btu4
            SEND btu4 NG_boiler4 TO Boiler4
        }
        else
        {
            btu4=btu4-Tot_BFG
            SEND Tot_BFG BFG_ent TO Boiler4
            bfgcon4 = Tot_BFG
            Tot_BFG = 0
            NG_4 = btu4
            SEND btu4 NG_boiler4 TO Boiler4
        }
    }
    else
    {
        NG_4 = 0
    }
}
1 High_Press_Steam HP_Steam    FIRST 1 MOVE ON Boiler_LP_Network

High_Press_Steam Boiler5    /*Logic for Boiler 5 pulling the required fuel*/
/*It will pull the BFG until its over and the remaining is satisfied by NG*/
if bol9 = clock(min) then
{
    bol9=bol9+1
    if Tot_BFG >=btu5 then
    {
        Tot_BFG = Tot_BFG - btu5
        SEND btu5 BFG_ent TO Boiler5
        bfgcon5 = btu5
        btu5=0
    }
    if Tot_BFG < btu5 then

```

```

        {
            if Tot_BFG <0 then
            {
                NG_5 = btu5
                SEND btu5 NG_boiler5 TO Boiler5
            }
            else
            {
                btu5=btu5-Tot_BFG
                SEND Tot_BFG BFG_ent TO Boiler5
                bfgcon5 = Tot_BFG
                Tot_BFG = 0
                NG_5 = btu5
                SEND btu5 NG_boiler5 TO Boiler5
            }
        }
        else
        {
            NG_5 = 0
        }
        NG_cumm = NG_tot
        NG_tot = NG_101+NG_102+NG_3+NG_4+NG_5+pi101+pi102+pi3+pi4+pi5
        NGcost = NG_tot * 5.5
        bfgcontot = bfgcon101+bfgcon102+bfgcon3+bfgcon4+bfgcon5
    }
    Tot_BFGgraph = Tot_BFG
    1 High_Press_Steam HP_Steam    FIRST 1 MOVE ON Boiler_LP_Network

High_Press_Steam HP_Steam    /*Calculation of HP header Pressure and KP steam in it*/
/*Opearion of #8 turbine*/
    if bol4 =clock(min) then
    {
        bol4=bol4+1

        HP_Steam_var=HP_Steam_var+Boiler_var101+Boiler_var102+Boiler_var3+Boiler_var4+Boiler_var5
        HP_Pressure = 1504.08 - (833.33*(18852/(HP_Steam_var*1000)))
        HP_Steam_var = HP_Steam_var - MW30
        SEND MW30 High_Press_Steam TO Turbine_30MW
        Join MW30 High_Press_Steam
        /*MW Generated*/
        MW30tur=0.3803*(MW30*0.9708)
    }
    HP_Steam_var1=HP_Steam_var
    tur30=MW30

    1 High_Press_Steam BP_Turbine6    SEND 1 MOVE ON Boiler_LP_Network

    High_Press_Steam De_Sup_Heater    SEND MOVE ON Boiler_LP_Network

    High_Press_Steam Turbine_30MW    SEND MOVE ON turbo_network
    High_Press_Steam Dummy_turbo    SEND MOVE ON turbo_network

    High_Press_Steam BP_Turbine9    SEND MOVE ON Boiler_LP_Network

High_Press_Steam BP_Turbine6

    1 LP_steam    Dummy_BP6    FIRST 1 MOVE ON Boiler_LP_Network

LP_steam    Dummy_BP6    1 LP_steam    LP    JOIN 1 MOVE ON Boiler_LP_Network

High_Press_Steam De_Sup_Heater
    1 LP_steam    Dummy_Desup_LP    FIRST 1 MOVE ON Boiler_LP_Network

LP_steam    Dummy_Desup_LP    /*for water addition
    watervar=0.1*desuperheater
    desuperheater=desuperheater-1*/
    1 LP_steam    LP    JOIN 1 MOVE ON Boiler_LP_Network

Water    De_Sup_Heater    1 Water    EXIT    FIRST 1
High_Press_Steam Turbine_30MW

```

		1	High_Press_Steam	EXIT	FIRST 1	MOVE ON Boiler_LP_Network
High_Press_Steam	BP_Turbine9	1	LP_steam	Dummy_BP9	FIRST 1	MOVE ON Boiler_LP_Network
LP_steam	Dummy_BP9	1	LP_steam	LP	JOIN 1	MOVE ON Boiler_LP_Network
LP_steam	LP	1	LP_steam	Dummy_LP_User	SEND 1	MOVE ON LP_User_Network
LP_steam	Dummy_LP_User					
		1	LP_steam	User	JOIN 1	MOVE ON LP_User_Network
Noise_ent	Noise	1	LP_steam	Noise	JOIN	MOVE ON LP_User_Network
			Noise_ent	EXIT	FIRST 1	MOVE ON LP_User_Network
High_Press_Steam	Dummy_turbo	1	High_Press_Steam	Turboblower	JOIN 1	MOVE ON turbo_network
turbo_ent	Turboblower					
						/*Operation of turbo blower*/
						if bol11 = clock(min) then
						{
						bol11=bol11+1
						turbo_blower = arrsetpt[7]
						SEND turbo_blower High_Press_Steam TO Dummy_turbo
						Join turbo_blower High_Press_Steam
						HP_Steam_var=HP_Steam_var-turbo_blower
						}
		1	turbo_ent	Combustion	FIRST 1	MOVE ON combustion_path
turbo_ent	Combustion	1	turbo_ent	EXIT	FIRST 1	MOVE ON combustion_path
BFG_ent	Boiler101	1	BFG_ent	EXIT	FIRST 1	MOVE ON BFG_path
BFG_ent	Boiler102	1	BFG_ent	EXIT	FIRST 1	MOVE ON BFG_path
BFG_ent	Boiler3	1	BFG_ent	EXIT	FIRST 1	MOVE ON BFG_path
BFG_ent	Boiler4	1	BFG_ent	EXIT	FIRST 1	MOVE ON BFG_path
BFG_ent	Boiler5	1	BFG_ent	EXIT	FIRST 1	MOVE ON BFG_path
BFG_ent	BFG_flaring	1	BFG_ent	EXIT	FIRST 1	MOVE ON BFG_path
BFG_ent	Combustion	1	BFG_ent	BFG	FIRST 1	MOVE ON BFG_path
NG_ent101	NG101	1	NG_ent101	DummyNG101	SEND 1	MOVE ON NG_path
NG_ent101	DummyNG101	1	NG_ent101	Boiler101	JOIN 1	MOVE ON NG_path
			NG_ent101	Pilot101	JOIN	MOVE ON NG_path
NG_boiler101	Boiler101	1	NG_boiler101	EXIT	FIRST 1	MOVE ON NG_path
Pilotent101	Pilot101					/*Operation of pilot for Boiler 101*/
						SEND 1 NG_ent101 TO DummyNG101
						Join 1 NG_ent101
		1	Pilotent101	EXIT	FIRST 1	MOVE ON NG_path
NG_ent102	NG102	1	NG_ent102	DummyNG102	SEND 1	MOVE ON NG_path102

```

NG_ent102    DummyNG102                1 NG_ent102    Boiler102    JOIN 1 MOVE ON NG_path102
NG_boiler102 Boiler102                NG_ent102    Pilot102    JOIN MOVE ON NG_path102
NG_boiler102 Boiler102                1 NG_boiler102 EXIT FIRST 1 MOVE ON NG_path102

Pilotent102 Pilot102 /*Operation of pilot for Boiler 102*/
SEND 1 NG_ent102 TO DummyNG102
Join 1 NG_ent102

1 Pilotent102 EXIT FIRST 1 MOVE ON NG_path102

NG_ent3      NG3                1 NG_ent3      DummyNG3      SEND 1 MOVE ON NG_path
NG_ent3      DummyNG3          1 NG_ent3      Boiler3      JOIN 1 MOVE ON NG_path
NG_boiler3    Boiler3          NG_ent3      Pilot3      JOIN MOVE ON NG_path
NG_boiler3    Boiler3          1 NG_boiler3    EXIT FIRST 1 MOVE ON NG_path

Pilotent3     Pilot3 /*Operation of pilot for Boiler 3*/
SEND 1 NG_ent3 TO DummyNG3
Join 1 NG_ent3

1 Pilotent3 EXIT FIRST 1 MOVE ON NG_path

NG_ent4      NG4                1 NG_ent4      DummyNG4      SEND 1 MOVE ON NG_path
NG_ent4      DummyNG4          1 NG_ent4      Boiler4      JOIN 1 MOVE ON NG_path
NG_boiler4    Boiler4          NG_ent4      Pilot4      JOIN MOVE ON NG_path
Pilotent4     Pilot4          1 NG_boiler4    EXIT FIRST 1 MOVE ON NG_path
/*Operation of pilot for Boiler 4*/
SEND 1 NG_ent4 TO DummyNG4
Join 1 NG_ent4 1 Pilotent4 EXIT FIRST 1 MOVE ON NG_path

NG_ent5      NG5                1 NG_ent5      DummyNG5      SEND 1 MOVE ON NG_path
NG_ent5      DummyNG5          1 NG_ent5      Boiler5      JOIN 1 MOVE ON NG_path
NG_boiler5    Boiler5          NG_ent5      Pilot5      JOIN MOVE ON NG_path
Pilotent5     Pilot5          1 NG_boiler5    EXIT FIRST 1 MOVE ON NG_path
/*Operation of pilot for Boiler 5*/
SEND 1 NG_ent5 TO DummyNG5
Join 1 NG_ent5

1 Pilotent5 EXIT FIRST 1 MOVE ON NG_path
1 BOP_Steam  BOP                1 BOP_Steam  Waste_heat_boiler FIRST 1 MOVE ON BOP_network

BOP_Steam     Waste_heat_boiler m1 = m1+1 1 LP_steam Tank FIRST 1 MOVE ON BOP_network

LP_steam      Tank /*Operation of Accumulator/Tank*/
if count1 = clock(min) then
{
count1=count1+1
Vent_var = (800/(200*60))*(tp-600)
if Vent_var<0 then
{
Vent_var=0
}
if Vent_var>arrsetpt[8] then
{
Vent_var=arrsetpt[8]
}
m=m+BOP_Steam_arrival-m2-Vent_var
/*This is specific Volume*/
sv=18852/(m*1000)
/*This is Tank Pressure. HP_Pressure calculated in same way*/
tp= 459/(sv**0.9923)
Total=Total+m2
Total_LP_Steam=Total_LP_Steam+m2
send m2 LP_Steam to LP
SEND Vent_var LP_Steam TO Vent
}
Total1 = Total
Ventgraph=Vent_var
mgraph=m

```


		1	LP_steam	LP	SEND 1	MOVE ON BOP_network
			LP_steam	Vent	ALT	MOVE ON BOP_network
LP_steam	Vent	1	LP_steam	EXIT	FIRST 1	MOVE ON LP_User_Network

Arrivals					
Entity	Location	Qty each	First Time	Occurrences	Frequency
User_requirement	User	arrsetpt[6]	0	inf	1 min
LP_Steam_arrival	LP	arrsetpt[6]	0	INF	1 min
BFG_ent	BFG	arrsetpt[12]	0	inf	1 min
BOP_Steam	BOP	BOP_Steam_arrival	0	INF	1 min
turbo_ent	Turboblower	arrsetpt[7]	0	inf	1 min
NG_boiler101	Boiler101	1; NG_arrival	0	inf	5 min
NG_boiler102	Boiler102	1; NG_arrival	0	inf	5 min
NG_boiler3	Boiler3	1; NG_arrival	0	inf	5 min
NG_boiler4	Boiler4	1; NG_arrival	0	inf	5 min
NG_boiler5	Boiler5	1; NG_arrival	0	inf	5 min
High_Press_Steam	Boiler101	Boiler_var101	0	inf	1 min
High_Press_Steam	Boiler102	Boiler_var102	0	inf	1 min
High_Press_Steam	Boiler3	Boiler_var3	0	inf	1 min
High_Press_Steam	Boiler4	Boiler_var4	0	inf	1 min
High_Press_Steam	Boiler5	Boiler_var5	0	inf	1 min
NG_ent101	NG101	arrsetpt[20]	0	inf	1 min
NG_ent102	NG102	arrsetpt[21]	0	inf	1 min
NG_ent3	NG3	arrsetpt[22]	0	inf	1 min
NG_ent4	NG4	arrsetpt[23]	0	inf	1 min
NG_ent5	NG5	arrsetpt[24]	0	inf	1 min
Stove_arrival	Stove	s1	0	inf	1 min
Stove_arrival2	Stove2	s2	0	INF	1 min
Noise_ent	Noise	Noise_var	0	inf	1 min
Pilotent101	Pilot101	arrsetpt[15]	0	inf	1 min
Pilotent102	Pilot102	arrsetpt[16]	0	inf	1 min
Pilotent3	Pilot3	arrsetpt[17]	0	inf	1 min
Pilotent4	Pilot4	arrsetpt[18]	0	inf	1 min
Pilotent5	Pilot5	arrsetpt[19]	0	inf	1 min
Water	De_Sup_Heater	1	0	inf	1 min

Arrays		
ID	Dimensions	Type
boparr	500	Real
Cummsec	500	Integer
arrsetpt	24	Real
arrboltur	30	Real

Arrivals				
ID	Qty / %	Cumulative	Time (Hours)	Value
NG_arrival	Quantity	No	1 min	g1
			2 min	g1
			3 min	g1
			4 min	g1
			5 min	g1