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AN OPTIMAL DESIGN OF A SOAKING PIT - ROLLING MILL SYSTEM

by

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9589

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1972

Approved by:

Major Professor

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ACKNOWLEDGEMENTS

The author wishes to thank his major advisor, Dr. Said Ashour for his untiring assistance in the completion of this thesis. Sincere thanks are also extended to Dr. L. E. Grosh for his help in the use of GASP-IIA and Mr. Stanley H. Baldwin for the invaluable insight given into the workings of an integrated steel plant.

As regards Ms. Marie Jirak who so ably and speedily brought out this copy, mere words fall short of the mark.

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CHAPTER I

INTRODUCTION

The iron and steel industry is considered one of the primary industries upon which the industrial development of a nation should be based. With the rapid changes in technology and rising competition, the iron and steel industry is facing a continuous challenge to produce the required products with the least cost. This cannot be achieved without the utilization of available resources and the productive equipment effectively and efficiently.

1.1 An Integrated Iron & Steel Plant

A brief description of an iron and steel plant with specific reference to the units of the system being studied would serve as an adequate introduction. The various stages will be classified either as productive units (units that markedly enhance the product status) or non-productive units (units that prepare the raw material for the next productive unit). Figure 1.1 is the production flow chart for a typical integrated iron and steel plant.

Productive Units

They are usually three main productive units in any iron and steel plant: (1) blast furnaces (2) steel works, and (3) rolling mills. In each of these units, the input product makes substantial progress towards the final finished product status. A large amount of literature in operations research exists on the productive units as compared to the

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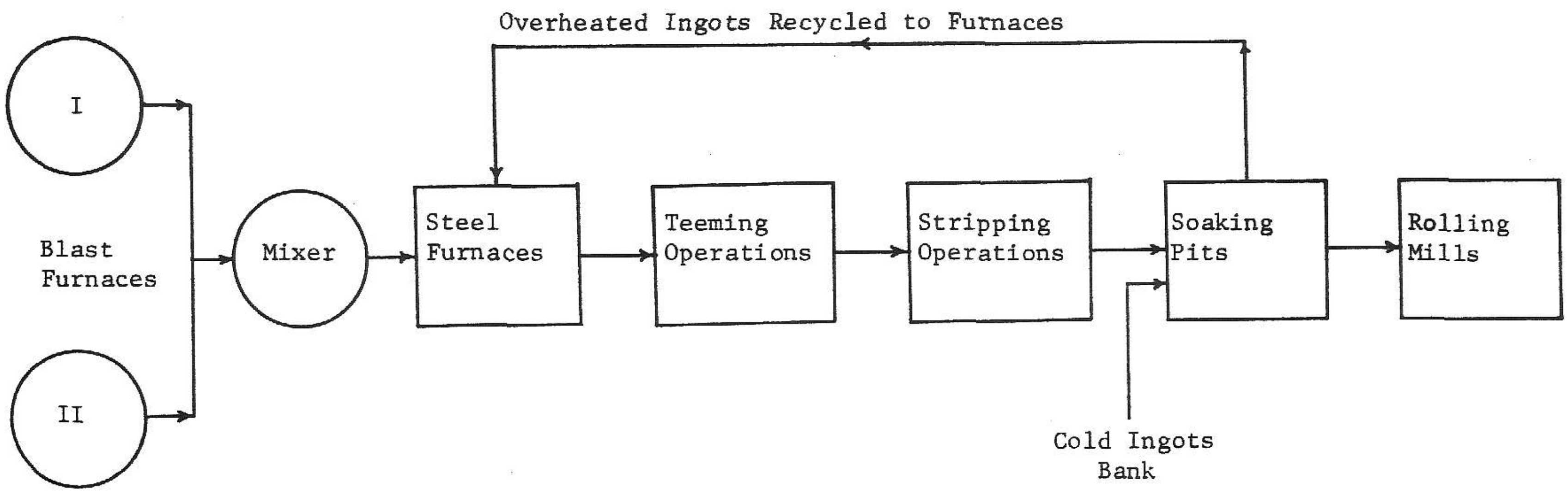

Figure 1.1 Flowchart of an Integrated Steel Plant

non-productive units. A brief description will facilitate further discussion.

Blast furnaces. The ingredients for the manufacture of iron, principally iron ore, limestone and coke are fired in a blast furnace resulting in the manufacture of pig iron. It takes about 6.8 tons of these raw materials (including 3.5 tons of air) to produce one ton of pig iron. The furnace auxilliaries are the gas mains, boiler, stoves, water lines, pumping station and the blowers. Each of these is a vital part of the system and a breakdown in any one would bring to a halt the working of the entire furnace complex. The hearth area multiplied by a factor of 2 to 2.6 depending on the raw materials, would give approximately the rated daily production in tons. Slips occuring within the furnace might lead to explosions and scaffolding of the charge might seriously damage the firebrick lining. Iron and steel plants have usually more than one furnace (generally two or three) so that the output of molten pig iron is not interrupted by mishaps.

Steel works. It consists of several furnaces and adjoining facilities for tapping the furnaces and teeming the molten metal into molds. If the ingots are cast in pits or at the ground level, a special stripping crane would be necessary to strip the ingots. However, if buggy casting is favored, the stripping may be performed in the soaking pit area itself as the ingots are cast atop the rail cars that transport them there. The basic open hearth process is overwhelmingly popular in the United States and accounts for almost 90% of the steel produced. Whatever the method used, proper planning and scheduling of the various operations will bring about increased production at insignificant cost.

Rolling mills. This is the stage in which the ingot is reduced to a round, oblong, square or some other simple shape. As the cross section of the ingot decreases, its length increases correspondingly. The resulting pieces are called blooms slabs and billets. There is no precise definition for any of these terms and tradition more than anything else decides the use of a particular term. Generally, the first mill that performs the reduction in the cross sectional area is called the blooming mill. The ingot is sequentially rolled by a series of mills till the finished product is arrived at. During the process it might be necessary to reheat the semi-finished product to the required degree of plasticity as there is a continuous loss of heat after the ingot leaves the soaking pit area. Each time the ingot goes between the rollers, it is said to make a pass and several passes are made by each mill before the product is ready for the next mill. The entire rolling mill section is an in-line process for the greater part and any stoppage of the blooming mill would necessitate idling of the other mills in the flowstream. Exceptions would be the finishing mills which have individual stockpiles of semi-finished rolled goods.

Non-productive Units.

The non-productive units, on the other hand, are: (1) molten metal mixer, and (2) soaking pits. The former unit is placed between the blast furnace and the steel works (melt shop) while the latter is located after the steel works immediately prior to the rolling mills. A functional description of these two units follows.

Molten metal mixer. It is a cylindrical, steel fabricated, refractory lined vessel mounted on rockers so that it can be tilted to disgorge the molten pig iron stored within. Its functions are threefold;

1. It conserves heat in the molten pig iron till the steel furnaces are ready to receive the charge. Auxilliary burners are often installed inside to maintain the molten state of the pig iron and make up for lost heat.

2. Succeeding outputs of a blast furnace vary in composition and more so the outputs from different furnaces. Significant structural variations within a batch of steel ingots are avoided by mixing the outputs of the blast furnaces. Thus, a uniformity in the composition and temperature of iron is promoted.

3. Due to its large capacity, it can permit independent operations between the blast furnaces and the steel making works, since any ordinary delay in the operation of one unit will not seriously affect the other. In this respect, its use is analogous to that of a flywheel with a large moment of inertia. For added safety, modern plants have two mixers of a smaller size each, rather than a single large one as a hedge against mixer breakdowns.

Mixer capacities have to be carefully calculated taking into consideration future increased production rates, if starvation of the steel furnaces is to be avoided.

Soaking pits. Briefly, they are refractory lined chambers or furnaces sunk into the ground wherein steel ingots are reheated to an optimum temperature and degree of plasticity before being processed by the blooming mills. The prime purpose is to reheat the ingot uniformly across its cross-section without overheating the surface. This is achieved by thermostatically controlling the temperature between $2150^{\circ}F$ and $2450^{\circ}F$($1176^{\circ}C$ and $1343^{\circ}C$) and permitting the ingot to 'gas soak', that is, heat at the same temperature that temperature equalization may take place.

The pit covers are generally steel fabricated and have a refractory shield suspended at the bottom to withstand the impingement of hot gasses. Sufficient insulation is provided between the shield and the lid to prevent heat losses. Electric motor operated mechanisms are provided to remove and replace the lid as rapidly as possible to conserve the heat. There are principally two types of soaking pits in contemporary use; the regenerative type and the recuperative type. In the regenerative type, the heat of the exhaust gasses is absorbed by the regenerator and later transferred to the air blast entering the burner in an alternate manner. However, the recuperator transfers heat continuously from the exhaust gasses to the incoming air blast through the use of heat exchangers.

A series of pits usually installed in rows are placed under cover of a building adjacent to the entering side of the blooming mill. The soaking pits are spanned by one or more electric traveling overhead cranes equipped with a traveling hoist for charging the ingots into the pits and lifting them out as they are needed by the mill. The lower end of this hoist is provided with adjustable tongs to grasp the ingot. The ingots arrive at the soaking pits atop rail cars or buggies after they have been stripped of their molds by a specially equipped stripper crane. For transporting reheated, ready to roll ingots, a pot car or ingot chariot is provided, which usually is electrically propelled along a track leading to the blooming mill tables, upon which it automatically deposits the ingots. This process is repeated continuously, the frequency of the transportation cycles keeping pace with the blooming mill operation.

1.2 Problem Definition.

The preceding discussion should make it apparent that greater efficiency in the non-productive units of the integrated iron and steel plant will necessarily result in increasing productivity and lowering the cost per ton of the finished products. This work will only deal with ways and means of increasing the efficiency in the soaking pit - rolling mill complex, however. This increase in efficiency would consist in finding the optimal capacity for the soaking pits based on a minimum cost of reheating the ingots. In keeping with the law of diminishing returns a stage would be reached when the return per dollar invested would start declining. Graphically, this point would be the minima of the curve representing the net cost of heating an ingot. It remains to be seen whether the net cost curve is flat in the region of the minima or not. A quick review of the intricacies involved in the reheating of ingots in the soaking pits will enable one to appreciate more fully the restricted solution space wherein an optimum has to be located.

In accordance with the well known formula, the heat transferred by conduction is given by

$$Q = K.T.A\ (t_1 - t_2)$$

where,

- Q heat transferred in kilo calories,
- T time during which the heat transfer takes place,
- A surface area subjected to heat transfer,
- (t_1-t_2) temperature gradient where t_1 is the temperature of the surface closest to the core of the ingot and t_2 is the temperature of the core of the ingot,
- K coefficient of thermal conductivity,

Though the formula used above is strictly valid only in the case of unidirectional heat flow, the fact remains that heat flow is a function of the temperature gradient. It follows that by maintaining t_1 as high as possible without letting the surface sweat, the greatest amount of heat can be transferred by conduction into the body of the ingot within the shortest possible time, other factors remaining constant.

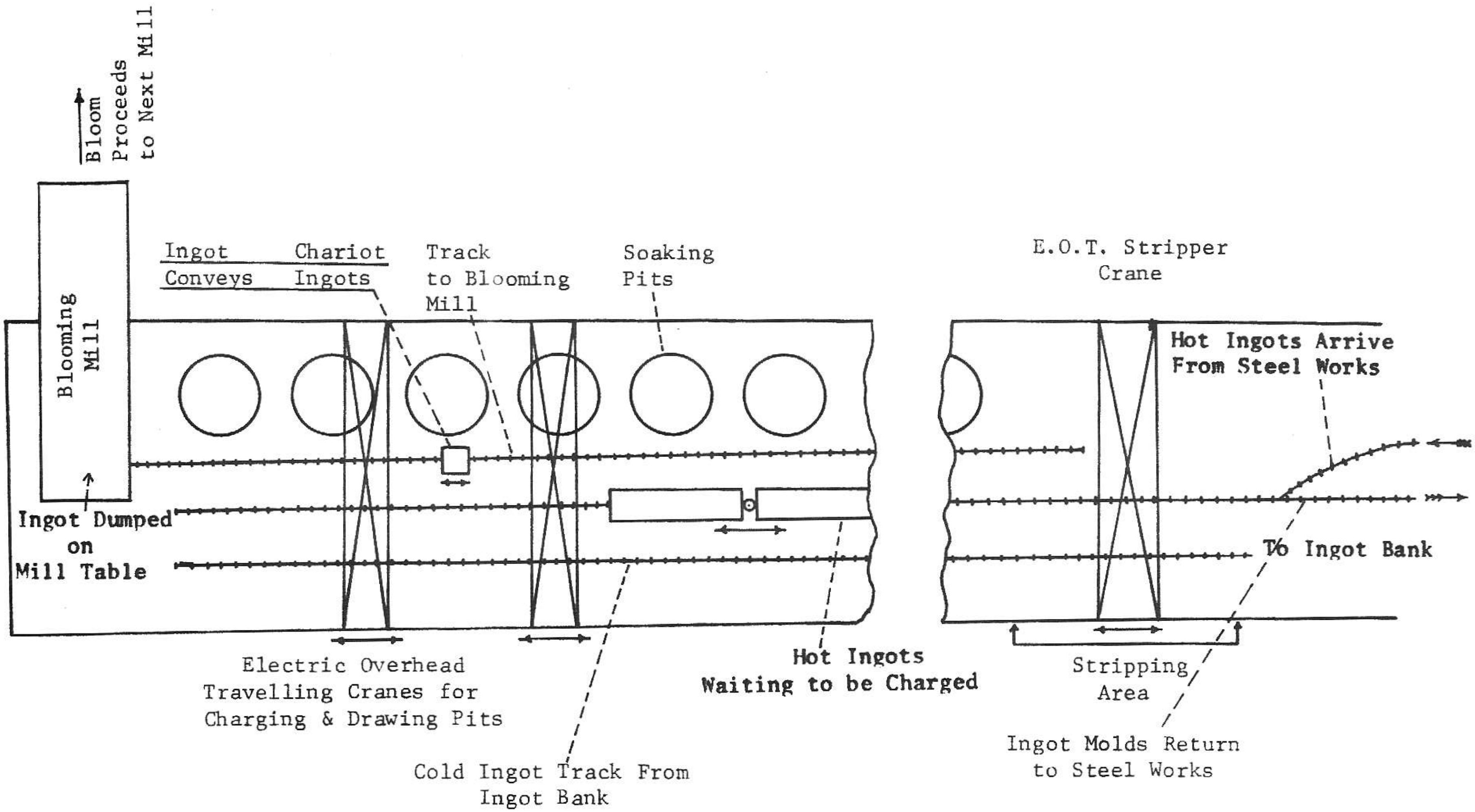

Figure 1.2 Layout of Soaking-Pit Area (not to Scale)

At the same time, as t_2 rises, the rate of conductive heat transfer would decrease necessitating a gradual lowering of the firing rate. Some time before t_2 reaches the critical rolling temperature t_c, the firing will have to be stopped altogether to allow for equalization of temperature over all sections of the ingot. At this stage, the existing temperature gradient would permit conductive heat transfer to the interior, t_1 and t_2 approaching t_c from opposite sides. Of course, t_1 would always be greater than t_2 while the ingot was gaining heat. This practice of getting uniformly heated products at a high rate even though uneven temperatures occured during firing is known as 'firing and dampering'.

Initial dampering is even more important in cases of very short track time where track time is defined as 'finish pour through complete charging' time. The spongy core of the ingot must be permitted to lose heat to the outer surface and solidify. The fuel is shut off and no draught of cold air is permitted within the pits. The larger the least dimension of the ingot, the longer should the dampering period be. The process effects a saving in time and fuel. The dampering time decreases with increasing track time. Alternately, minimum track times may be set to insure complete solidification of the ingot core. The track time would then be a function of the pouring temperature and the least dimension of the ingot. Ingots may be stripped at the pouring shed itself or later on at the soaking pit area. The latter is preferrable if the track time is of considerable magnitude as ingot heat losses are prevented to a great extent by stripping the ingots just prior to charging. In the design and operation of a modern soaking pit the following objectives are paramount.

1. Ingots in soaking pits must be reheated uniformly without having any excessively hot spots on any of the ingots.

2. The operating cost of the soaking pits must be a minimum.

3. The initial capital expenditure should be reasonably low.

4. Soaking pits should be as compact as possible without sacrificing any heating capacity.

5. The soaking pits must be able to cope up with the blooming mill requirements.

6. The duplication of reheating of different batches of ingots must be possible.

7. Control of the atmosphere in which the ingots are heated must be possible.

The first objective is the prime purpose of the soaking pits. Objectives 2, 3, and 4 call for reduced expenditure while objectives 5, 6, and 7 define a floor level for the reduction beyond which any further reduction in the net total cost is impossible. Thus, starvation of the rolling section would be the result of inadequate soaking pit capacity while an oversized capacity would entail unnecessary capital expenditure as well as increased operating costs. To put it in terms of costs, a balance between the cost of service and the cost of waiting for that service has to be achieved. The variable part of the cost of service is the operational cost per unit output and that part of the output installation that depends on the size and the number of the soaking pits. The cost of waiting depends on the inventory costs, the cost of the heat lost by ingots waiting to be charged to the pits and the cost of 'cold steel', that is, the idle time of the blooming mill due to the non-availability of ready-to-roll ingots. The scope and extent of this investigation is to determine the "best" capacity of soaking pits such that the total cost is minimized.

1.3 Literature Survey

The first point that strikes a researcher in this field is the diverse objectives of the various investigators, although the basic aim in all cases is to increase the efficiency at some point or the other. Reddy [16] has primarily been interested in increasing the throughput of the pit-mill complex. His approach to achieving this end consists primarily in instituting arbitrary criteria based on sound common sense in the crane operation with respect to the soaking pits. Brancher, Stringer and Savage [4] have the same objective but they have concentrated, to a greater extent, on reducing the track time of the ingot batches arriving at the soaking pit area. In fact, a judicious application of the critical path method brought about substantial reduction in track time and hence the heating time.

Hindson and Sibakin [9] have also been concerned with increasing the throughput but with particular attention paid to the correlation of the ingot temperatures with the maximum permissible draft and the number of passes required. Their findings clearly indicate that light drafts result in a time loss by increasing the number of passes while too heavy drafts result in time losses by increasing the number of trippings of the blooming mill motor. Consistent drafting at the safe maximum limit is conducive to a greater throughput.

All previously mentioned authors agree clearly on one point, namely, in the absence of exact knowledge of the rate of cooling and heating of ingots, empirical relations are successfully being used in the predetermination of heating time in soaking pits as a function of the track time of the ingots. This is largely due to the non-availability of accurate surface pyrometers in the 700° to $1350^{\circ}C$ range as Brancker, Stringer and Savage [4] have pointed out. Further, it is mentioned that knowledge of a technique to establish the precise temperature distribution through an ingot at anytime and the cooling rates of stripped ingots as well as the heating rates of charged ingots under various furnace conditions, would lead to greater control over the soaking pit practice.

In their recent publication entitled "A Mathematical Model of Soaking Pits", Kung, Dahm and DeLancey [10] have established minimum ingot heating times based on the knowledge of the temperature distribution in the ingots at the time of charging. This in turn implies that the cooling rate of the ingots after teeming must also be known. The obvious drawback to this approach is the difficulty in determining the various heat transfer coefficients as well as the dimensionless empirical quantities. These would necessarily be determined by a particular setup and type of equipment. In addition, some of the assumptions made are approximations of the existing situation so that an analytical solution to this approximation can, at best, be an approximate answer to the original problem. Nevertheless, the approach is a break through of sorts.

So far the emphasis had been on gaining more information about the heat content and heating rate of the ingots being charged to the soaking pits in order to arrive at a minimum fuel expenditure. Buzacott and Callahan [5] struck off in another direction and have concentrated on keeping the blooming mill busy and increasing the throughput. They have made use of a closed cycle queueing model proposed by Posner and Bernholtz [13, 14] in arriving at an expression for the probability of the mill being idle for want of hot steel. This expression turned out to be a function of the number of soaking pits, the product of the mill rate and the reheat delay of the pits. Though it appears to be rather attractive due to its simplicity, its limitations shall be explained in the next chapter.

Mellor and Tocher [11] devised a steelworks production game by building a computer simulation model of the steelworks and then validating the model with the co-operation of the plant management. This model is useful in predicting the utilization and efficiency of various parts of the complex and testing human reactions to various situations. The primary purpose, however, is to demonstrate the advantages of continuous central control.

As the above mentioned publications have been studied, two points crystalized: (1) each setup has been investigated as a unique problem; and (2) none of these have been aimed at arriving at a soaking pit capacity based on a minimum reheating cost per finished ton.

1.4 Proposed Research

The investigation with which this paper is concerned is limited to the pit-mill complex of an integrated iron and steel plant. The principle aim is to find the optimal reheating capacity given a particular production rate. The pit-mill complex will be viewed as a cyclic queueing process in which the blooming mill and a crane are represented as a single service station and the set of soaking pits are the units in the system needing service.

Due to the complexity of the process, a simulation model will be developed in which various factors such as furnace breakdown and repair, mill and crane breakdowns, soaking pit operations, rules governing interactions between the cranes, pits and the mill, among others, are taken into consideration. Several experiments under varying conditions will be conducted to study the effects of various factors. In order to find the optimal reheating capacity, all other factors will be fixed at certain levels with varying only the number of pits for each of a series of experiments. A sensitivity analysis of the system's behavior with changing number of pits will be made and conclusions drawn. A secondary objective would be to compare the results obtained analytically from a cyclic queueing model with the simulation results.

CHAPTER II

PIT-MILL SHOP-LIKE QUEUEING MODEL

The system with which this paper is concerned is best analyzed if the various processes in the soaking pit area are viewed as forming part of a queueing network with the inputs and outputs governed by certain laws and assumptions. This will help analyze the problem in all its aspects.

The soaking pit area can be represented as a closed cycle with a single service station and m units needing service moving in a cyclic fashion. The units in this model are the soaking pits, each of which holds a certain number of ingots according to some probability distribution function. The service station is considered as a combination of the blooming mill and an overhead crane. When a pit is ready to receive service, an available crane unloads the pit, one ingot at a time, the ingot chariot carrying the ingot to the blooming mill table and returning for the next ingot and so on. The time taken to draw a pit is in effect the time to process the pitload of ingots by the blooming mill. This is the service time, its mean value being $1/\mu$ where μ is the mean service rate, assuming an exponential service time. A crane can charge or draw a soaking pit. The pit is said to be "in transit" as soon as it leaves the service station.

The arrival of ingots from the steelworks is batchwise and the number of ingots per batch is randomly distributed. The arrival rate of the batches and hence, the interarrival time follows a certain probability distribution. The pit in transit is charged with ingots arrived from the steelworks, if any, or with cold ingots from the ingot bank. The pit then starts reheating the ingots and the transit time, denoted by H*, ends as soon as the pit-load of ingots reaches the rolling temperature. Thus the transit time H* is a sum of the charging time and the reheating time. The pit then joins the queue awaiting service, with the maximum queue length being m. The arrival rate of the pits at the blooming mill queue follows a certain probability distribution function.

At any given time there will be ℓ, $\ell = 1, 2, \ldots, m$, pits in transit and $(m-\ell)$ pits awaiting service or being served. It should be noted that if the service station is always busy, the maximum length of the queue would have been (m-1). However, there is a possibility of one of either cranes or the pit, as well as any combination of the three units breaking down or forced to be idled for some other reasons. Likewise, for the number of pits in transit to be equal to zero, the transit time will have to be less than the service time $1/\mu$. This is a near impossibility as the minimum heating time itself is several times larger than the mean service time. Only a breakdown of the blooming mill, while it is in operation, would give rise to this contingency. Figure 2.1 gives a diagrammatic view of the soaking pit operations as a closed cyclic queueing network with a single-channel, single server.

A general cyclic queueing model developed by Posner & Bernholtz [13] might provide an approximate analytical solution to the model described in this work. The general model will be described first, after which the pit-mill model will be considered as a special case of the general model, and its solution described.

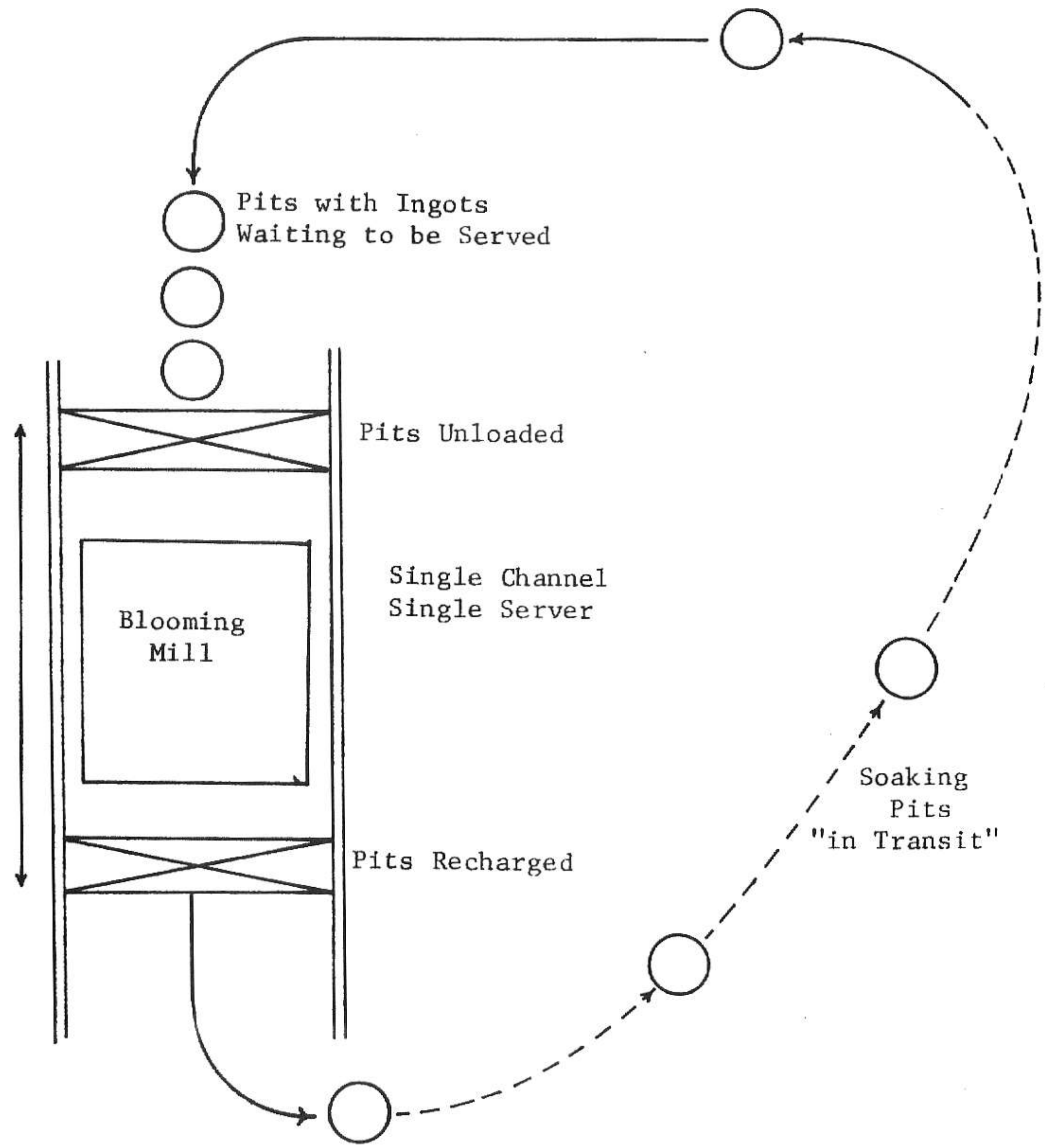

Figure 2.1 Cyclic Queueing Simulation Model

Consider a finite closed cycle queueing system in which m identical units move among 1,2,...,N stations. A unit completing service at station i moves to station j (i,j = 1,2, ..., N) with probability e_{ji}. If there is no queue and the server is idle, the unit is serviced immediately. However, if there is a queue, the unit awaits service in the queue. Following are the assumptions made in arriving at the general model.

1. All units in the system are identical. Every unit has the same set of parameters for service at the stations, and the same set of travel time distributions between stations and the same routing procedures.
2. There is a definite time lag between the time a unit finishes service at one station and arrives at the next. This transit time has a definite distribution function.
3. The service times at each station are independent, exponentially distributed random variables.
4. The instantaneous service rate at a station is an arbitrary function of the number of units awaiting service at that station.

The vector state $\underline{Z}(t)$ at any time t is a function of the following three variables:

1. $\underline{I}(t)$, a vector function that denotes the number of units at station r, r = 1,2, ..., N, at time t.
2. $[A(r,s,t)]$, an NxN matrix giving the number of units in transit between any two stations r and s at time t, where $r, s \in N^*$, $N^* = \{n | n = 1,2, \ldots, N\}$.

3. $[\underline{X}_{A(r,s,t)}]$, an NxN matrix of the elapsed in-transit times for the A(r,s,t) units on path (r,s) at time t.

Thus,

$$\underline{Z}(t) = \{\underline{I}(t);\ [A(r,s,t)];\ [\underline{X}_{A(r,s,t}]\},$$

and the probability element of the state variables at time t is given by $f^t(\underline{i};\ [a];\ [\underline{x}])\ d[\underline{x}]$ where the lower case variables denote the values of the random variables designated by the upper case.

Consider a specific state $\underline{z}(t+h)$ at time t+h of the most general form in which (1) there is at least one unit at each station and at least one unit in transit on each path at time t+h, and (2) no unit in transit at time t+h has an elapsed in-transit time less than h.

The first step in obtaining the integro-differential difference equations is to arrive at expressions for a transition from state $\underline{z}(t)$ at time t to the specific state $\underline{z}(t+h)$ at time t+h. In doing this, it is recalled that the process of arrivals and service completion of units at every station represent pairwise independent events. Using these results, the Chapman-Kolmogoroff equations (a generalization of the equations describing Markoff chains) which give $f^{t+h}\ (\underline{i};\ [a];\ [\underline{x}])$ in terms of f^t can be arrived at.

Assuming that f^t has all the jointly continuous derivatives required, it can be shown by using a multiple Taylor's expansion of the right hand side of the Chapman-Kolmogoroff equations involving f^t and by taking limits on both sides as $h \to 0$ that the general integro-differential difference equations of the process are:

$$\left\{ \frac{\partial}{\partial t} + \sum_{r=1}^{N} \mu_r(i_r) + \sum_{r=1}^{N} \sum_{s=1}^{N} \sum_{k=1}^{a(r,s)} \left[g_{r,s}\,(x_k^{r,s}) + \frac{\partial}{\partial x_k^{r,s}} \right] \right\}$$

$$f^t(\underline{i};\ [a];\ [\underline{x}]) = \sum_{r=1}^{N} \sum_{s=1}^{N} \sum_{k=0}^{a(r,s)} \int_{\tau=x_k^{r,s}}^{x_{k+1}^{r,s}} f^t(\underline{i}_s -;\ [a] +;\ [\underline{x}]_{r,s};$$

$$(\underline{x}_{a(r,s)})_\tau)\ g_{r,s}(\tau)\ d\tau$$

where, i_r, $a(r,s) > 0$ for all r, s ε N*, and $S(\underline{i}) + S([a]) = m$

The boundary equations corresponding to the cases in which at least one of the stations has no units either waiting or in service and/or at least one pair of stations has no units in transit between them, are derived similarly.

Recall that it was initially assumed that no unit in transit at time t + h has an elapsed time less than h. If one of the elapsed times does violate this assumption, additional boundary equations will have to be found. Of course, this can occur if and only if a service had been completed at station r during the interval [t, t+h] and the unit is subsequently directed toward station s along path (r,s). The assumption is then made that the events of a service completion, and subsequent selection of a path are independent. Combining the general and boundary equations yields the complete set of integro-differential difference equations. In addition, the probability normalizing condition holds for all $t \geq 0$ namely, $f^t(\underline{i};\ [a];\ [\underline{x}])\ d[\underline{x}]$ summed over the entire range is equal to one.

In order that the steady state for the above system of equations exist, the following conditions must be satisfied.

1. The mean rate of departure from each station s, $s \in N^*$, is equal to the mean rate of arrival of units at station s along all paths directed towards that station.

2. The mean rates of entry and departure of units along any path of the system must be equal.

3. The steady state is totally independent of initial conditions.

If V_s^* denotes the mean rate of unit departure from station s, then

$$V_s^* = \sum_{r=1}^{N} V_r^* e_{s/r}, \qquad \text{for all } s \in N^*$$

The unique steady state solution can be such that

$$f(\underline{i};\ [a];\ [\underline{x}]) = C_0 \left(\prod_{r=1}^{N} B_r(i_r) \right) \left(\prod_{r=1}^{N} \prod_{s=1}^{N} \prod_{k=0}^{a(r,s)} \{e_{r,s}[1 - G_{r,s}(x_k^{r,s})]\} \right)$$

and

$$\frac{1}{C_0} = \sum_{S(\underline{i})=0}^{m} \cdots \sum \left(\prod_{r=1}^{N} B_r(i_r) \right) \left\{ \frac{H^{*m-S(\underline{i})}}{(m-S(\underline{i}))!} \right\}$$

where

H^* the expected duration of the time lag that a unit which has just completed service at one of the stations must undergo.

C_0 a constant with respect to the elements of $[\underline{x}]$, $C_0 = C(0,0,\ldots,0)$.

$$B_r(i_r) = \frac{V_r^{i_r}}{\prod_{k=0}^{i_r} \mu_r(k)}$$

The marginal joint probability that there are i_r units at station r, $r \in N^*$ is denoted by

$$P(\underline{i}) = P(i_1, i_2, \ldots, i_N).$$

By integrating out all vectors $\underline{X}_{a(u,v)}$, and summing over all (u,v), where $u, v \in N^*$ in the steady state equation such that $S([a]) = m - S(\underline{i})$, it can be shown that

$$P(\underline{i}) = C_0 \left(\prod_{r=1}^{N} B_r(i_r) \right) \frac{H^{*m-S(\underline{i})}}{(m-S(\underline{i}))!}, \text{ for } S(\underline{i}) \leq m.$$

The pit-mill complex may now be considered as a special case of the general model described above. There is one service station, the mill, $N = 1$ and m units, the soaking pits all of the same class. The mill serves all the pits at the same rate μ.

The mean transit time of a pit, H^* is defined as the sum of the time it takes to charge the pit and the heating time of the ingots. This transit time may be redefined to include the time taken to overhaul the pits. Suppose p is the probability that a soaking pit completing a cycle needs overhaul and suppose that the expected time required to overhaul the pit is R. Then, the expected transit time is given by $H = bR + H^*$. This value of the transit time may be used in steady state probability calculations. Let

$$i_j = \begin{cases} 1, & \text{if pit j is waiting or being drawn,} \\ 0, & \text{otherwise.} \end{cases}$$

and

$$S(\underline{i}) = i_1 + i_2 + \ldots + i_m.$$

Since all the pits are considered identical, $S(\underline{i}) = i$, where i is the number of pits in the waiting line or being served; thus

$$P(\underline{i}) = P(i)$$

where i is the total number of pits waiting or being served by the mill. Let V_r be the probability that a unit was last served at station r such that

$$V_r \begin{cases} 1, & \text{if } r = 1 \\ 0, & \text{if } r \neq 1 \end{cases}$$

and

$$1/\mu_r(k) = 1/\mu,$$

as there is only one station and one class of units being served.

The simplified queueing network to fit the mathematical model is shown in Figure 2.2. With the above values, the general steady state equation may be simplified to

$$P(i) = \frac{m!}{(m-i)!} \frac{1}{(\mu H^*)^i} \left\{ \sum_{k=0}^{m} \frac{m!}{(m-k)!} \frac{1}{(\mu H^*)^k} \right\}^{-1}$$

and

$$Q = P(0) = \left\{ \sum_{k=0}^{m} \frac{m!}{(m-k)!} \frac{1}{(\mu H^*)^k} \right\}^{-1}$$

where P(0) is the probability that no pits are either waiting or being serviced by the mill and the mill is idle for want of hot ingots.

It is seen from the above expression that factors affecting the

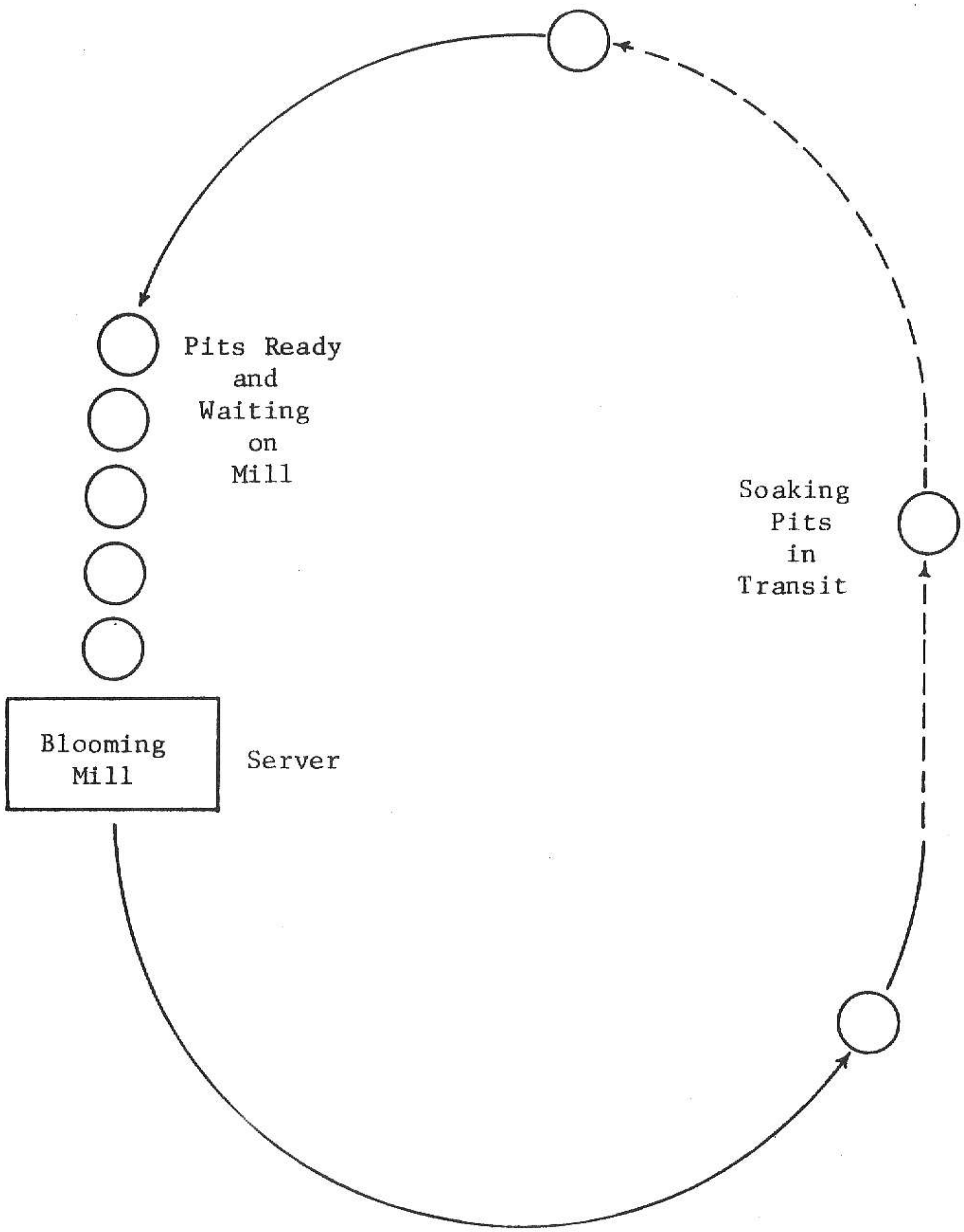

Figure 2.2 Cyclic Queueing Analytical Model

extent of cold steel delays are the number of soaking pits and the product of the blooming mill rolling rate and the heating time of the ingots in the pits. Consequently, the capacity of the pit-mill complex is given by

$$\bar{\mu} = (1 - Q)\ \mu.$$

It should be fairly clear by now that the analytical approach to dynamic systems uses differential equations. The relationships between the elements of the subsystems are expressed as algebraic relationships between differentials with the assumption that the variables and their derivatives are continuous and the relationships are stable over time. However, most real life situations are stochastic (randomly varying with respect to time) by nature. In a simulation, these properties might be modelled explicitly for the subsystems whereas a mathematical approach to the same problem is dependent on having truly representative values for the transit time and the service time. Each of these in turn is dependent on factors such as (1) track time, (2) crane and mill operating status, (3) crane operating priorities, and (4) ingot arrival patterns and frequencies. The ingot arrivals themselves are functions of the operating status of the steel furnaces in the steelworks.

While it is feasible to impute certain distributions and parametric values to each of the above subsystems, it would be presumptious to arrive at expected values for μ and H^* as a result of the interaction of all these factors. Thus, the analytical approach to a problem of this nature would give "an exact answer to an approximate problem", to quote N. J. Reddy [16] and recalling that the simplified network for application of the mathematical model is not a true functional replica of the queueing network shown in Figure 2.1.

The desirability for simulating the process is more so when it becomes necessary to impute cost factors to the measures of performance of the system's components so that a minimum cost of reheating ingots is obtained. For these reasons it would appear that a persuance of the objective using computer simulation would prove more fruitful. However, in one of the experiments conducted with the simulation model, equivalent values shall be substituted in the mathematical model as far as is feasible, and a comparison of the results made.

CHAPTER III

DEVELOPMENT OF A SIMULATION MODEL

Simulation is a method for predicting the dynamic characteristics of a system to improve the basis for the decision process. This chapter is devoted to describing a simulation model developed to investigate the soaking pit - rolling mill complex. The assumptions made in developing this model are introduced. Various measures of performance including the economics of ingot reheating are also discussed.

3.1 Model Description

Modelling involves two broad subtasks: the creation of a structure and supplying the data. In the course of establishing the structure, the system boundaries are clearly defined and separated from the system environment. For example, in the flow-chart of the simulation program shown in Figure 3.1 the arrival of the charge to fill the steel furnaces is part of the system environment whereas the arrival of the ingots at the soaking pit area is a part of the system structure. Any object that is of interest in the system will be termed an entity having one or more attributes. An activity changes the state of the system as exists at a given point in time to another state. The entities, attributes and activities of the model being investigated are listed in Table 3.1.

It will be observed that certain events occur within the system, such as the completion of heating a pitload of ingots. These are called endogenous events as opposed to exogenous events that take place outside the system boundaries but nevertheless affect the system. An example

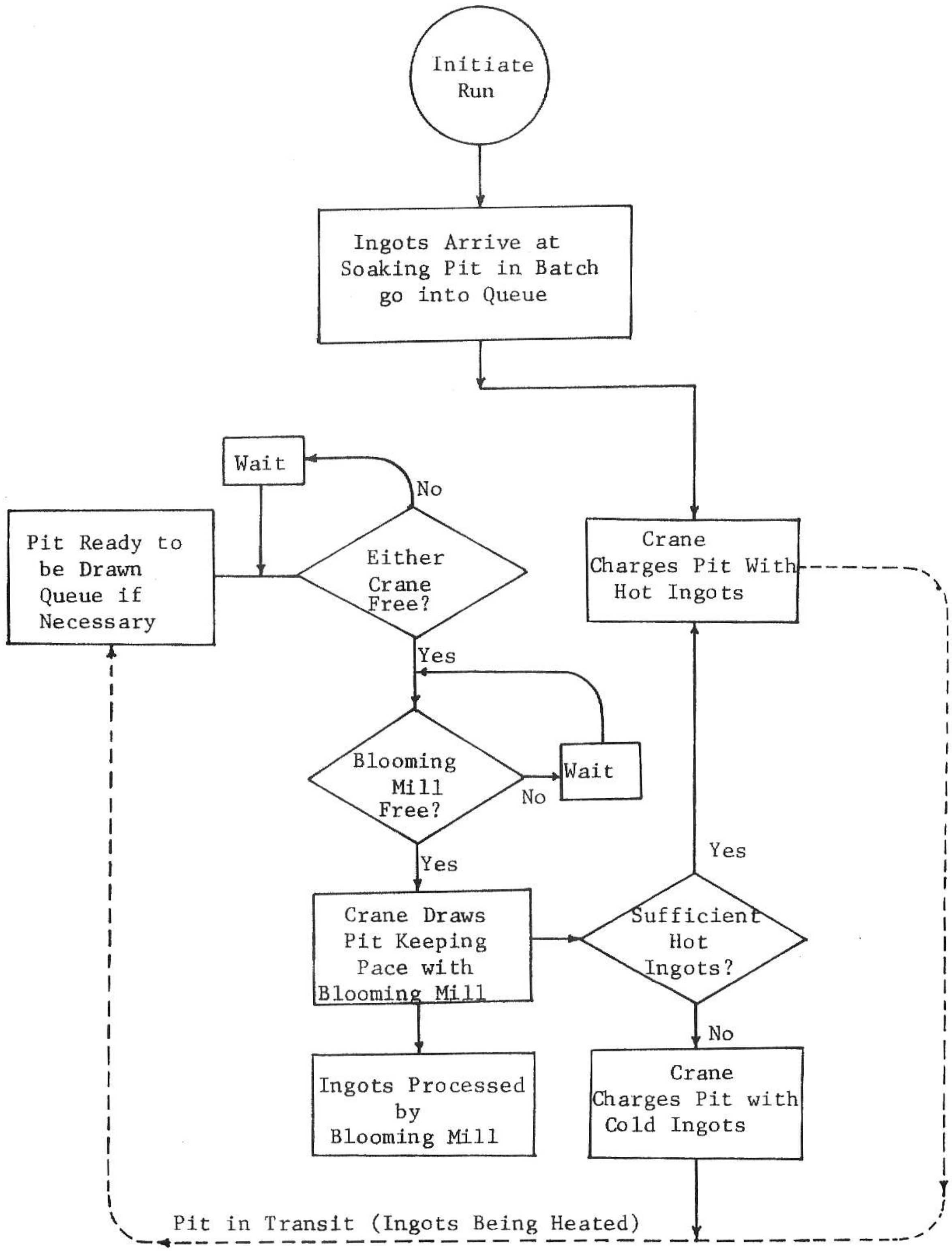

Figure 3.1 Event Flowchart of Soaking-Pit Area of Simulation Model.

Table 3.1 Soaking-Pit Model—Simulation Elements.

ENTITY	ATTRIBUTES	ACTIVITIES
Ingots	Furnace identification number.	Arrival at soaking pits.
	Time of arrival.	
	Batch size.	
Steelworks Furnace	Heat number.	Pour a batch of ingots.
		Overhaul for maintenance.
Soaking Pits	Time of completion of heating.	Heat ingots.
	Pit number (serial).	
	Pit status (idle or busy).	
	Number of ingots heated.	
Cranes	Crane number (serial).	Empty pit.
	Crane status (busy, idle or breakdown).	Recharge pit, get overhauled.
Blooming Mill	Status (busy, idle or breakdown).	Process ingots.

is power failure that would hold up the entities in the system. The system is an 'open' one as exogenous activites affect it. If this were not the case it would be termed a closed system.

The organization of advance of time in a simulation process cannot be overemphasized. A 'continuous time simulation' would require a flow of time in uniform, discrete quantities mimicking a continuous flow. The system is updated and operating characteristics noted before each time advancement. This method is more suitable for analog computers than digital ones. The time keeping method used here can be described by the term 'discrete-event simulation'. The time axis is broken into discrete intervals that occur between 'events' or points of interaction between entities. An event is defined as a particular happening that changes the state of the system in a discrete quantity though the true life process may be a continuous one. The measures of the system are taken at event times and are discrete in nature. For instance, though the reheating of ingots in a soaking pit is a continuous process, the event of reheating is accomplished only at the end of the process and the simulation clock is advanced by a discrete quantity of time representing the duration of heating. The intervals are not necessarily equal. The advantage in employing this method of time advancement is that the futility of system updating for minuscule changes is eliminated especially when these small changes are of little significance. In other words, it is sufficient to examine the system at event times in order to understand the behavior of the system.

The principle events considered in this simulation are:

1. The arrival of a batchload of ingots.
2. The arrival time of a furnace overhauling contingency.
3. The end of reheating of a batch of ingots by a soaking pit.
4. The end of drawing and charging a pit by one of the cranes.
5. The earliest time the blooming mill is free after rolling a pitload of ingots.

An explanation of the flow logic of the model along with the assumptions made to simplify the simulation, will give a clear insight.

Arrival of ingots at the soaking pit area is batchwise. Each furnace at the steelworks is capable of putting out a certain number of heats before it goes in for re-lining; when it does so, a previously idled furnace is activated which then takes the place of the furnace being idled. The range of the batch size depends on whether a 100 ton or a 150 ton furnace has teemed the currently arriving batch. The number of ingots in each batch is a random variable.

The arriving ingots are immediately queued up for a simple reason, the avoidance of keeping the crane and hence the blooming mill idle. If at the time that a pit is totally drawn, there are insufficient or no ingots freshly arrived from the steelworks, cold ingots are charged instead. On the other hand, a long waiting line of hot ingots from the steelworks would result in expensive loss of heat. Hence, an information feedback loop is instituted and the interarrival time of the ingot batches made a function of the number of ingots in the queue.

As soon as one of the two cranes is free, a check is made to see if any of the soaking pits is ready for drawing. If one of the cranes is available, the free crane proceeds to unload the pit. However, if both cranes are free, the crane with a higher priority over the pit will attend to the pit. This is done to avoid the possibility, as far as possible, of one of the cranes being blocked by the other. If no pits are available, the crane has to remain idle until a pit gets ready, at which time a check is made on the status of the blooming mill. If the blooming mill is inoperative, the crane and the pit wait till it does become operative. A figure of five percent has been widely accepted as the percentage inoperative time of the crane by the steel industry [9]. The value used in this model, however, is the average of the readings taken over a period of five years at the Kansas City steel works visited, both for the cranes and the blooming mill. Tables 3.2 and 3.3 display the values for the years 1966 through 1970.

The unloading time has been observed to be about a hundred seconds for each ingot. This is also the rolling time per ingot, as the unloading process alternates with the rolling ingotwise. Thus the unloading rate in effect gives the throughput rate.

The ingot queue is then checked. If there are sufficient 'hot' ingots waiting*, they are charged to the pit; otherwise, cold ingots from the ingot bank are charged into the pit. These cold ingots are imported from the outside and the mean rate of consumption of cold and hot ingots is 900 tons every 8-hour shift. The heating time of the ingots is a function of the track time as will be explained later.

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*Based on discussions with Mr. S. Baldwin of a steel company in Kansas City during my visit.

Table 3.2 Blooming Mill Downtime Statistics at a Kansas City Steelworks

Period	Mill & Size Change Delay %	Cold Steel Delay %	Total Delay %
1966	5.05	1.79	6.84
1967	4.30	1.81	6.11
1968	4.06	1.65	5.71
1969	3.98	2.76	6.74
1970	4.57	1.49	6.06
Jan.	4.45	1.80	6.33
Feb.	3.70	0.72	4.42
March	3.10	1.96	5.06
April	3.00	1.50	4.50
May	2.84	1.60	4.44
June	4.52	0.79	5.31
July	5.50	0.27	5.77
Aug.	4.59	2.54	7.13
Sept.	6.00	1.91	7.91
Oct.	5.86	2.50	8.36
Nov.	6.18	1.19	7.37
Dec.	5.43	1.02	6.45

Grand average of Mill & Size change delay, 1966 through 1970 is 4.392%

Table 3.3 Crane Downtime Statistics at a Kansas City Steelworks

Period	Electrical Breakdown %	Mechanical Breakdown %	Total Downtime %
1966	1.25	2.46	3.71
1967	1.27	2.83	4.10
1968	1.37	2.36	3.73
1969	1.58	3.30	4.88
1970	3.28	5.62	8.90
	Jan. - 6.20	7.30	13.50
	Feb. - 6.05	3.51	9.56
	March - 1.93	4.50	6.43
	April - 4.03	3.06	7.09
	May - 2.13	8.38	10.51
	June - 2.99	5.44	8.43
	July - 1.69	9.03	10.72
	Aug. - 4.37	8.29	12.66
	Sept. - 4.99	5.15	10.14
	Oct. - 1.62	3.60	5.22
	Nov. - 2.49	5.02	7.51
	Dec. - 2.95	4.74	7.69

Grand average of total downtime from 1966 through 1970 is 5.064%

The maximum heating time, of course, is the same as that for cold ingots, that is, six hours on the average.

As soon as a pitload of ingots is ready to be drawn, the crane status is checked and if the crane is available the mill status is checked. Only if a crane is free and the mill is functioning does the process of unloading the pit begin. Otherwise the pit joins a queue. Similarly, if a crane becomes available, the waiting line of the pits is checked and if a pit is available, the mill status is checked. Figure 3.2 is a bar graph showing relative activities of the two cranes and the mill along a time scale. Thus, it is seen that the model has two distinct phases. The first phase deals with the arrival of ingots, and generation of new arrivals. The second phase constitutes the heart of the model and processes ingots through the pit-mill complex. The latter phase is actuated by one of the three events — a pitload of ingots getting ready or a crane being freed or the completion by the mill of processing a pit load of ingots. The occurrence of one of these three events sets into motion a series of logically sequenced interactions between the cranes, pits, ingots and the mill.

A noteworthy point is that the breakdown of the cranes and the mill are mutually independent random variables. Hence, the periods of idling may overlap. If T_c denotes crane downtime and T_m denotes mill downtime, then the total downtime T_d is such that $T_d = T_c \cup T_m$. The computer program provides for this eventuality.

Ingot heating time. There are several formulae available that calculate the heating time of ingots in pits as a function of the track time.

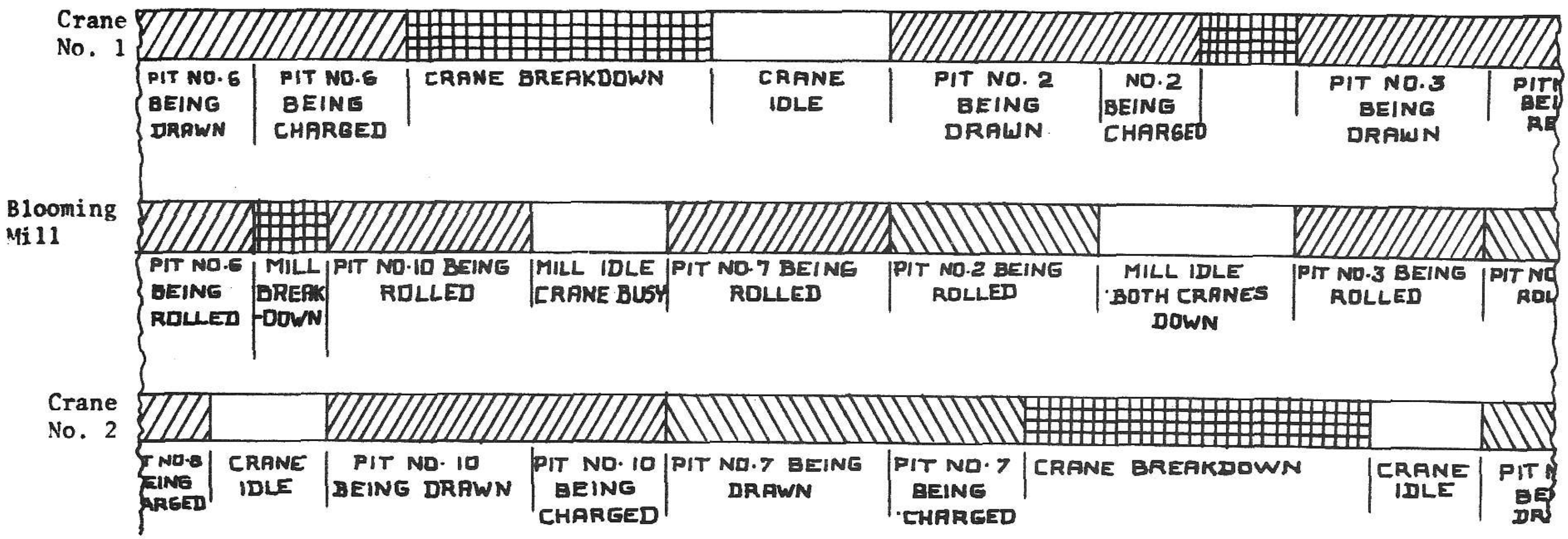

Figure 3.2 Gantt Chart Showing Relative Activities of the Two Cranes and Blooming Mill (not to scale).

These are empirical relations that have been arrived at by plotting the heating time against the track time and are found to be practically useful, at various soaking pit installations. Almost all of them are linear relations of the form y = mx + c, where y is the heating time, x the track time, m of the order of 0.5 to 1 and c ranges 0-2. On this basis, a linear equation shall be used in this simulation to calculate the heating time. The values of the parameters m and c depend on several variables such as the shape and size of the ingots, the rate of firing of the soaking pits, the ambient temperature and the type of rolled products and composition of steel. It would not be incorrect to say that each installation is unique for the determination of the heating time.

In the problem under consideration, it was noted that: (1) cold ingots were heated for an average of 6 hours, (2) freshly arrived ingots were treated as 'cold' if the track time exceeded 4 hours, and (3) the minimum time in the pit was 1.75 hours. With these three conditions, the value of m is equal to 1.06. The heating time will then be given by the expression.

Heating time = 1.06 (track time) + 1.75

Figure 3.3 shows a graph of heating time versus the track time.

Assumptions. The assumptions under which the simulation is conducted are:

1. No allowance shall be made for a decreasing rate of activity during shift changes. All parts of the complex are assumed to be uniformly active around the clock.

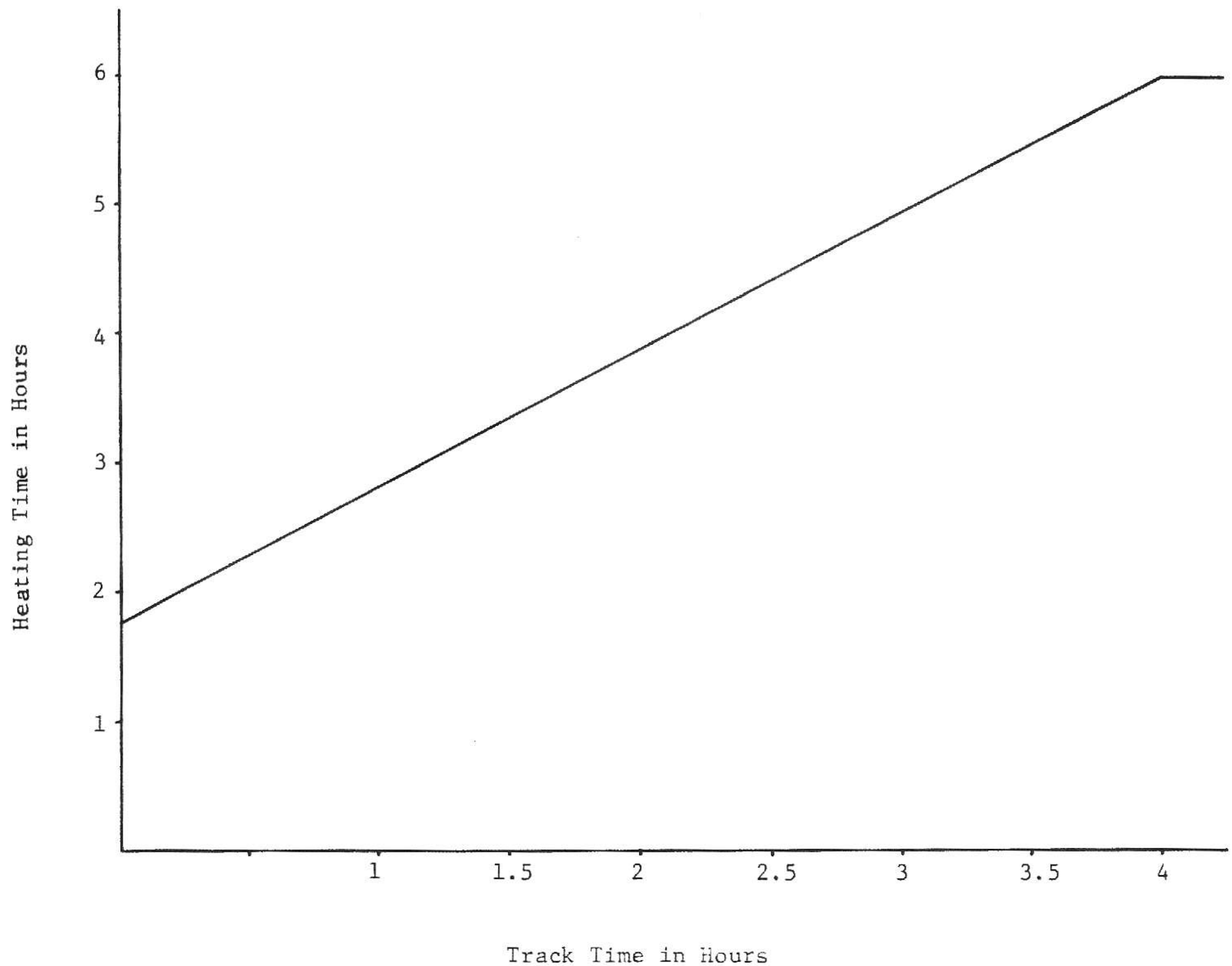

Figure 3.3 Heating Time of Ingots as a Function of the Track Time.

2. The pit maintenance time has not been considered owing to insufficient data.
3. The crane traveling time between pits has not been deemed significant enough to warrant inclusion in the model.
4. The firing rate for a pit waiting to be drawn is 20 per cent of the full firing rate. This heat is supplied only to make up for heat losses from the waiting pit.
5. As a policy of preventive maintenance is followed, not more than one furnace is idle at any time. Time allowances are not made for breaking in a newly lined furnace.
6. The percentage breakdown times for the cranes and the blooming mill involve a policy of preventive maintenance. Repairs are started when a crane becomes idle but may not end in time for it to report to duty when called upon. Thus, the program does not provide for the contingency of the crane breaking down when it is in the process of drawing or charging a pit.
7. The crane operators are assumed to have full information about the pits' status. They know which of the pits are ready to be drawn and the order in which the pits got ready. Thus the pits can be serviced on a 'first-come, first-served' basis.
8. A pit cannot hold more than 16 ingots.

3.2 Operating Characteristics

The operating characteristics of the system are recognized by collecting appropriate statistics at suitable times, generally whenever a discrete change occurs in the system. Two kinds of statistics can be collected. When the value of a variable persists over a period of time, one is interested, not only in the value of the variable, but also in the length of time the variable assumed that value; such statistics are said to be time-weighted. On the other hand, when the value of a variable is a sample value of an attribute, the statistics is said to be non-weighted. Time-weighted statistics are taken to calculate the following measures of performance.

1. The average number of ingots in the system.
2. The utilization of each of the two cranes.
3. Average number of ingots waiting to be charged to the soaking pits.
4. Average number of soaking pits waiting to be serviced by the cranes.
5. Average number of ingots heated in each pit.
6. The utilization of each soaking pit.

Non-weighted statistics are collected to determine the following.

1. Average waiting time of the ingots before being charged to to the soaking pits.
2. Average waiting time of the ingots before being drawn from the soaking pits.

In addition, the following measures are computed at regular intervals throughout the simulation run.

1. Average heating time of ingots.
2. The various costs involved in the process.

The last mentioned measure warrants detailed explanation forthwith given.

Cost analysis. The study of this problem is extended to include various cost analyses. In doing so, it will be necessary to determine the cost per ton of finished steel. This cost consists of two parts; (1) a fixed cost that does not vary with the reheating capacity, and (2) a variable cost that varies with the reheating capacity of the soaking pit. Cost comparisons can therefore be made after computing only the variable cost of finished steel per ton. The components of the variable cost are:

1. The capital cost of adding a soaking pit along with all its auxilliaries.
2. The cost of running the pit such as labor, fuel and electricity.
3. The maintenance cost for the pit including the cost of repair materials and labor charges.
4. The cost of an idle blooming mill.

It will now be explained how excessive or insufficient pit capacity affects the variable part of the cost of finished steel, or simply, cost per ton. Thus, if the mill produces x tons of steel in a given period of time at a cost of y, then y/x is the variable cost per ton. As mentioned earlier, the objective in this study is to minimize the cost per ton.

The capital cost in adding a pit is a large one, of the order of half a million dollars and includes the pit auxilliaries. Obviously, the increased capital expenditure must be offset by increased output if the cost per ton is not to increase. With regard to the cost of running an extra pit, it stands to reason that added pit capacity results in increased fuel expenditure even if the output remains constant. Putting it differently, fuel consumption would not be directly proportional to the output tonnage as one would expect in an ideal situation. A percentage of the total fuel and electricity supplied is a function of the output tonnage. The remainder varies as the number of pits and is used in heating up cold pits, making up pit heat losses and the unavoidable wastages connected with pit operation. It must be noted that the former need not vary linearly as the production tonnage. Assuming that the output has not changed inspite of an increased heating capacity, it would naturally result in a shorter waiting time for ingots queueing up to be charged. Consequently, the heating time in the pits would be reduced. The precise relation is difficult to predict, as, not only the pit characteristics have to be considered, but also the delays resulting from crane and mill operation policies.

With regard to the cost of maintaining an additional soaking pit, in the absence of detailed records, it is reasonable to assume that the cost of items such as labor, repair supplies (fireproof cement, high quality refractories, etc.) varies directly as the number of soaking pits in the long run.

The blooming mill downtime cost consists of three distinct components. The first is the cost due to idle labor and capital. Some of the units in the complex would not be affected as they have their own stock of semi-finished products to be further processed while other units form a direct "in line" queue behind the blooming mill so that starvation of the blooming mill would starve these other units too. Thus, an indeterminate percentage of the labor force and capital equipment would be idle and precise record keeping would be necessary to arrive at this cost. The second is the cost of lost opportunity and is the value of the finished products that might have been turned out were the mill not idle. The third component is the intangible part of the cost of lost opportunity and is the result of loss of goodwill and future orders for not fulfilling standing orders on time. Penalty costs may be included in this category. In the absence of extensive information, intangible costs are not considered.

The following costs data* refers to the plant whose soaking pit area has been modelled for this investigation.

1. The production for the year 1970 was 900,000 finished tons. This works out to 900 tons per 8 hour shift and there are 1000 shifts available in a year.
2. The capital cost of a soaking pit of the type already installed would be $475,000 including all auxilliaries. Pits are depreciated over a period of 15 years with no scrap value at the end. The existing setup had 12 pits.
3. The fuel consumption at "high fire" (full load) is 28,000 to 30,000 cubic feet per hour. At low fire, the consumption is a fifth of the full load value.
4. The maintenance cost was $0.37 per ton for the year 1970.
5. The downtime cost of the blooming mill, not including the opportunity cost, was $671.00 per hour for the year 1970.
6. The average price for the finished products was $230 a ton for 1970.

*Based on discussions with Mr. S. Baldwin of a steel company in Kansas City during my visit.

The following notation are used in arriving at expressions for the component costs:

$\hat{m}$ = number of pits in the plant when the above data was collected.

m = number of pits assumed in the experiment.

H_s = number of production hours simulated.

$\hat{H}$ = total number of production hours available in a year.

n = total number of ingots processed during the experiment.

a = recovery weight of an ingot (in tons).

w = weight of steel rolled per hour (in tons).

J_i = total number of pitloads of ingots heated by the i-th pit, $i = 1,2, \ldots, m$

$H_h(i,j)$ = heating time of the j-th pitload of the i-th pit.

$H_w(i,j)$ = waiting time of the j-th pitload of the i-th pit.

H_d = mill downtime (in hours).

c_p = capital cost per pit per year

c_f = fuel cost per pit per hour

c_o = opportunity cost per hour of mill downtime.

c_d = establishment cost due to mill downtime

Now the following cost factors can be computed such that

1. Capital cost per ton,

$$C_p^m = m \cdot \frac{c_p}{na} \cdot \frac{H_s}{\hat{H}}$$

This indicates that the cost of the soaking pits per hour is multiplied by the number of hours of production simulated and divided by the total tonnage produced during this time.

2. Fuel cost per ton,

$$C_f^m = \frac{1}{na}\left\{\sum_{i=1}^{m}\sum_{j=1}^{J_i} H_h(i,j)\cdot c_f + \sum_{i=1}^{m}\sum_{j=1}^{J_i} H_w(i,j)\cdot 0.2\ c_f\right\}$$

This indicates that the total cost of fuel used by all the pits over all the pitloads, both while heating at high fire and waiting at low fire, is divided by the total tonnage produced during the run.

3. Maintenance cost per ton,

$$C_r^m = C_r^{\hat{m}}\cdot\frac{m}{\hat{m}}\cdot\frac{wH_s}{na}$$

This indicates that the maintenance cost per ton is directly proportional to the ratio increase in heating capacity and inversely proportional to the ratio increase in finished tonnage, with the constant of proportionality being the original maintenance cost per ton.

4. Downtime cost per ton,

$$C_\ell^m = \frac{H_d}{na}\cdot\{c_d + c_o\}$$

This indicates that the lost production time is multiplied by the sum of the establishment and opportunity costs and divided by the tonnage produced.

The variable cost per ton of finished steel which is a function of the reheating capacity is

$$C^m = C_p^m + C_f^m + C_r^m + C_\ell^m$$

or in words, the cost per finished ton is the sum of the capital cost, the fuel cost, the maintenance cost and the cost of blooming mill downtime — all of them on a "per ton of finished steel" basis.

CHAPTER IV

EXPERIMENTAL INVESTIGATION

The investigation comprises four sets of experiments. The number of soaking pits is the only factor to vary within each set of experiments. Each experiment consists of simulating the model described in the previous chapter for a certain time on the simulation clock. Computer runs made for Sets A and B will be discussed together and similarly, with Sets C and D. This is convenient as Set A differs from Set B only in the service discipline for arriving ingots as does C from D. A comparison will be made between the simulation results obtained in Set A and the analytical results obtained as explained in Chapter 2.

4.1 Computational Experiments

The simulation model has several independent variables that are termed factors. Table 4.1 lists the important ones. Some of these factors are uncontrolled because it is not known if the distributions used are the exact ones for the processes. They are qualitative in nature and have been included to increase the precision of the model. However, some control has been exercised by using previously observed values as some of the parameters. Variables 5, 6 and 7 of Table 4.2 fall in this category. Their levels were purposefully set from previously observed values as they were expected to significantly affect the response (dependent) variables. Variables 1,2,4 and 9 are totally controlled. Appendix A lists the quantitative factors, that is,

Table 4.1 Description of Principle Variables and Their Values in the Four Sets of Experiments

Variables	Set A	Set B	Set C	Set D
1. Discipline by which hot ingots arriving at the soaking pit area are charged.	FCFS	LCFS	FCFS	LCFS
2. Minimum number of ingots that may be charged to a soaking pit.	8	8	8	8
3. Inter-arrival time distribution for batches of ingots from the same furnace.	Exponential* $\mu = 3.25$	Exponential* $\mu = 3.25$	Erlang 4* $\mu = 3.25$	Erlang 4* $\mu = 3.25$
4. Heating time for hot ingots arriving from steelworks, H. (x is the track time).	$1.06x + 1.75$	$1.06x + 1.75$	$1.06x + 1.75$	$1.06x + 1.75$
5. Heating time distribution for cold ingots from ingot bank.	Uniform [5.5,6.5]	Uniform [5.5,6.5]	Uniform [5.5,6.5]	Uniform [5.5,6.5]
6. Inter-occurrence time distribution for crane breakdowns.	Exponential* $\mu = 0.6$	Exponential* $\mu = 0.6$	Erlang 4* $\mu = 0.6$	Erlang 4* $\mu = 0.6$
7. Inter-occurrence time distribution for mill breakdowns.	Exponential* $\mu = 0.39$	Exponential* $\mu = 0.39$	Erlang 4* $\mu = 0.39$	Erlang 4* $\mu = 0.39$
8. Distribution of number of heats produced by a furnace in between successive overhauls.	Uniform [10,12]	Uniform [10,21]	Uniform [10,21]	Uniform [10,21]
9. Queue discipline for pits waiting to be drawn.	FCFS	FCFS	FCFS	FCFS

* See Appendix D for histograms of generated frequencies.

Table 4.2 Simulation Results

Set	No. of Pits in Set	Mean Crane Utilization	Average Waiting Time of Ingots (Hrs.)	Average Waiting Time of S. Pits (Hrs.)	Average no. of Ingots in Queue	Average no. of Pits in Queue	Average Heating Time of Hot Ingots (Hrs.)	Average Heating Time of All Ingots (Hrs.)	Ratio of Ingots Charged Cold/Hot	Average no. of Ingots in System	Input Rate into the System (Tons/Hr.)	Output Rate from the System Tons/Hr.)	Fuel Cost per Ton ($/Ton)	Capital Cost per Ton ($/Ton)	Maint-enance Cost per Ton ($/Ton)	Down Time Cost per Ton ($/Ton)	Total Variable Cost per Ton ($/Ton)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	12	0.764	1.21	1.31	30.6	2.73	2.96	3.5	0.256	211	117.4	117.3	0.616	0.40	0.37	16.44	17.83
Set A	14	0.779	1.04	2.12	26.4	4.74	2.79	3.5	0.284	211	120.2	120.3	0.632	0.46	0.42	11.46	12.98
	15	0.747	1.03	2.58	28.2	5.89	2.78	3.49	0.284	216	120.0	120.0	0.645	0.49	0.45	11.20	12.50
	16	0.747	1.03	3.03	28.1	6.81	2.78	3.49	0.286	217	120.2	120.2	0.658	0.53	0.48	11.01	12.68
	17	0.748	1.05	3.46	26.7	7.64	2.80	3.52	0.286	221	120.2	120.1	0.674	0.56	0.51	11.19	12.94
	18	0.780	1.03	3.95	26.1	8.75	2.78	3.49	0.285	228	120.1	120.1	0.686	0.59	0.54	11.23	13.06
	20	0.781	1.01	4.88	26.7	10.71	2.76	3.48	0.285	235	120.1	120.0	0.712	0.66	0.60	11.41	13.40
	12	0.771	1.08	1.40	27.4	2.95	2.71	3.40	0.268	207	118.5	118.4	0.596	0.40	0.37	14.37	15.74
Set B	14	0.747	1.04	2.18	27.4	4.83	2.70	3.44	0.285	212	120.1	120.0	0.625	0.46	0.42	11.33	12.84
	15	0.747	1.03	2.63	28.1	5.92	2.69	3.43	0.286	216	120.2	120.2	0.637	0.49	0.45	10.98	12.57
	16	0.780	1.01	3.08	27.6	6.91	2.68	3.42	0.286	216	120.2	120.2	0.651	0.53	0.48	11.02	12.68
	17	0.746	1.04	3.53	26.4	7.77	2.70	3.43	0.285	221	120.1	120.1	0.667	0.56	0.51	11.26	13.01
	18	0.781	1.04	3.97	26.3	8.81	2.70	3.43	0.285	226	120.3	120.2	0.681	0.59	0.54	11.05	12.87
	20	0.747	1.03	4.91	26.1	10.78	2.70	3.43	0.285	236	120.1	120.0	0.709	0.66	0.61	11.36	13.34
	12	0.733	0.98	0.99	15.9	1.77	2.73	4.20	0.982	195	106.8	106.9	0.748	0.44	0.41	35.97	37.57
Set C	14	0.769	0.89	1.53	14.7	3.09	2.65	4.39	1.086	200	112.5	112.5	0.774	0.49	0.45	25.42	27.14
	15	0.743	0.87	1.90	14.3	4.08	2.62	4.40	1.114	203	114.0	114.1	0.787	0.52	0.48	22.56	24.35
	16	0.781	0.86	2.36	14.2	4.95	2.61	4.40	1.117	204	114.2	114.2	0.801	0.55	0.51	22.26	24.14
	17	0.778	0.88	2.82	14.4	5.93	2.63	4.41	1.114	209	114.0	114.1	0.817	0.59	0.54	22.49	24.17
	18	0.778	0.88	3.29	13.4	6.84	2.63	4.41	1.118	215	114.2	114.2	0.832	0.62	0.57	22.16	24.18
	20	0.744	0.91	4.28	14.9	8.93	2.66	4.42	1.111	225	113.8	113.9	0.862	0.70	0.64	22.83	25.03
	12	0.735	0.97	0.982	14.7	1.76	2.70	4.34	0.985	194	107.0	107.0	0.747	0.44	0.41	35.73	37.33
Set D	14	0.773	0.90	1.505	13.7	3.06	2.62	4.38	1.092	199	112.8	112.8	0.774	0.49	0.45	24.77	26.49
	15	0.779	0.88	1.903	14.4	3.90	2.61	4.39	1.108	203	113.6	113.7	0.788	0.52	0.48	23.11	24.90
	16	0.745	0.88	2.363	14.6	4.94	2.61	4.40	1.114	204	114.0	114.0	0.803	0.56	0.51	22.61	24.48
	17	0.777	0.88	2.818	14.6	5.84	2.61	4.40	1.117	209	114.2	114.2	0.817	0.59	0.54	22.20	24.18
	18	0.747	0.88	3.330	14.5	6.96	2.62	4.40	1.109	216	113.7	113.8	0.832	0.63	0.57	23.04	25.07
	20	0.781	0.89	4.266	14.7	9.00	2.62	4.41	1.113	224	113.9	114.0	0.861	0.69	0.64	22.60	24.80

factors whose levels are expected to affect the response variables. The only controlled factor whose response is well studied is the number of soaking pits within a set of experiments and to a lesser extent, the service discipline for arriving ingots.

In this context, the factor of the number of pits can be termed a fixed factor within a particular set. This is not to imply that all the levels of that factor have been investigated; but, knowing the nature of the response (in this case, the total variable cost) to be unimodal, it was deemed sufficient to run experiments in the vicinity of the minima. On the other hand the service disciplines, namely, first-come, first-served (FCFS) employed in Sets A and C, and last-come, first-served (LCFS) employed in Sets B and D are arbitrarily chosen from a population of levels for that factor. This does not constitute an exhaustive search and inferences drawn from investigating these levels of that 'random' factor apply only to the two levels experimented with.

Steady State. The responses of interest in this investigation are measured when the system has reached a steady state. The transient stage being of no interest, statistical files and arrays are cleared when the system's equilibrium is ascertained. In order to minimize the time lapse before the onset of steady state conditions, experimentally obtained steady state values are used in the initialization of each experimental run. Identical starting conditions have been maintained for all the experiments in all the four sets so that the approximate time for re-setting the statistical arrays for future experiments might be predetermined to facilitate the collection of steady state statistics. The use of identical sets of random numbers is prompted by the same interest as well as to sharpen the contrast between computer runs, having less to worry about differences introduced into responses by a different set of random numbers.

The important question is what should be the criteria for recognition of steady state. It must be recalled that the model has some subsystems so that not all the interesting responses would become steady at the same time depending on the cyclic period of the subsystems influencing these responses. It has been noted that most of these measures of performance such as crane utilization, queue lengths, waiting times and mean number of ingots in the system stabilize after about fifty hours of simulation time. Pilot runs have been made for all the sets to insure this, see Figures 4.17 through 4.20. Further, it is noted that changing the number of pits in an experiment does not have much affect on the time needed to attain equilibrium. It was decided to error on the safe side as well as provide a safety margin should the transient state linger in any experiment and a hundred hours were permitted to elapse before the statistical arrays were cleared to collect steady state statistics. This decision has resulted in no significant loss of time as, even at that value, the transient period comprises less than seven percent of the run time.

Length of Simulation Run. The length of each run is a compromise between the necessity to reduce random error and the need to minimize computer time. The primary response (total variable cost per ton) which is a function of the mill downtime fluctuated considerably for a long period. This can be explained by the results which indicate that even a little idling of the mill causes significant increase in the cost per ton. By a process of trial-and-error it has been decided to run each experiment for 1500 hours on the simulation clock. The collection of statistics being a cumulative process, the random variation at the end of this period is within acceptable limits. Needless to mention, if greater accuracy is warranted, the simulation time can be further increased to improve the stochastic convergence.

Experiments Conducted. In each set, the minimum number of soaking pits was initially assumed to exist somewhere between twelve and twenty. A sequential search for the minimum was made between these two points. Once the minimum was narrowed down to a small set of possibilities, an exhaustive search was made in that region. As it turned out, seven experiments were conducted in each set - twenty eight in all. Resulting total cost curves can be seen in Figures 4.7 (Sets A and B) and 4.15 (Sets C and D).

4.2 Experimental Results

Table 4.2 is a comprehensive representation of the results obtained from all the four sets of experiments. Figures 4.1 through 4.7 show graphs of selected measures of performance for Sets A and B as a function of the number of soaking pits. The total variable cost curve depicted in Figure 4.7 has a shape that was expected and is characteristic of cost curves. The penalty for not having sufficient reheating capacity far exceeds the extra cost incurred by erring on the safer side, that is, having excessive reheating capacity. Set A has a unimodal curve with a minima for sixteen pits while Set B has a minima for fifteen pits; see Column 18 of Table 4.2. There appears to be a random error in the experiment conducted for seventeen pits in Set B. As mentioned earlier, the total cost curve was the slowest to converge and no doubt better results can be obtained by increasing the length of each run, say, upto two thousand hours. Moreover, the error is of the order of two percent of the expected value which is an acceptable figure.

A noteworthy point is that an idle mill contributes the largest towards increasing the cost per ton. Fuel cost, capital cost and maintenance cost together constitute only about fifteen percent of the total cost. This is to be expected as the entire production of the rolling mill complex has to pass through the blooming mill at first and the maximum number of the working hours for the blooming mill itself constitutes an upper limit for production. Thus, any effort aimed at reducing mill idle time would be rewarding. Further, it is observed that the cost of service, namely, fuel, capital expenditure and maintenance increases monotonically with an increase in the number of soaking pits. However, the cost of waiting for this service does not decrease monotonically as was hypothesized. This anomalous behavior can be explained as follows.

Figure 4.6 shows a steep increase in production rate till the optimum value of the number of pits is reached. Thereafter, the production rate is obviously limited by mill and crane performance and the curve flattens out. With the production rate being fairly constant, the only factor that can increase the downtime cost is an increase in the idle time of the mill. Each time the mill completes processing a pitload of ingots, several conditions have to be fulfilled before it can commence processing the next pitload of ingots. For instance, a pitload of ingots has to be ready and waiting and at least one crane has to be free and functioning. The mill itself must not be due for any change of rollers or overhauling. Thus, there is a chance of the mill being idled for one reason or the other after it rolls a pitload of ingots. It must be recalled that mill breakdown during operation on a pitload of ingots has been excluded from the model.

It follows then that with a constant output rate, increasing the number of pits would result in a reduction in the utilization of soaking pits and, a greater number of pitloads would be supplying the same number of ingots. Figure 4.16 shows the mean utilization of soaking pits falling with an increase in the number of pits. As a result, a larger number of interactions take place between the entities of the system resulting in a slightly increased downtime. The cost of downtime per ton of finished steel, therefore, increases slightly (Column 17 of Table 4.2) with an increase in the number of pits after the minima for the total cost curve has been reached.

Pit utilization in the vicinity of the minima appears to be more steady than when away from it; see Figure 4.16. This reinforces the general conclusion emerging that in the region of the minima the sensitivity of the system to changing number of pits is not as great as when away from it. The waiting time of ingots is hardly affected by increasing the reheating capacity in both Sets A and B. However, the waiting time of pits before being drawn varies linearly as the number of pits, see Figure 4.2 and Columns 4 and 5 of Table 4.2. The average number of ingots in queue, likewise, undergoes marginal reduction in both Sets A and B but the number of pits in queue registers a steep linear increase with the number of pits, see Columns 6 and 7 of Table 4.2 and Figure 4.3. Contrary to expectations, increasing the number of pits does not decrease the tracktime and hence the heating time significantly. However, a three percent decrease in heating time (Column 9) for ingots arriving from steelworks only has been effected in Set B where the ingots were charged on a LCFS basis. Inspite of this, the minimum variable cost for both the sets remains almost equal. The average number of ingots in the system has registered an increase of about eleven percent over the entire range of experiments in both Sets.

A point of contrast between Sets A and B is that prior to the optima being reached there is a significant difference between the values of most of the measures of performance. This difference between the corresponding points for the two sets narrows as the optima is reached and thereafter the curves for both the sets practically coincide. Thus, the service discipline has an effect, if there are less than the optimal number of pits in a steelworks.

A comparison will now be made between the results obtained via simulation and those obtained by the analytical model discussed in Chapter II. As discussed earlier in this Chapter, mill idling is caused by one or more of the following three factors:

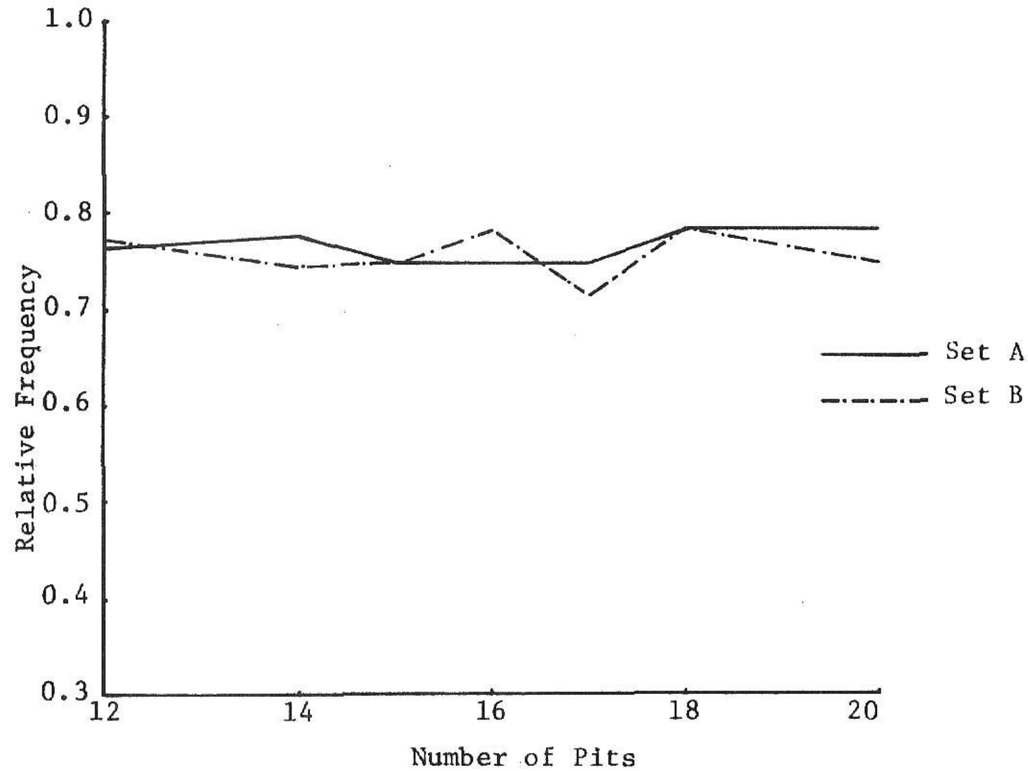

Figure 4.1. Relation Between Crane Utilization and Number of Pits in Sets A and B.

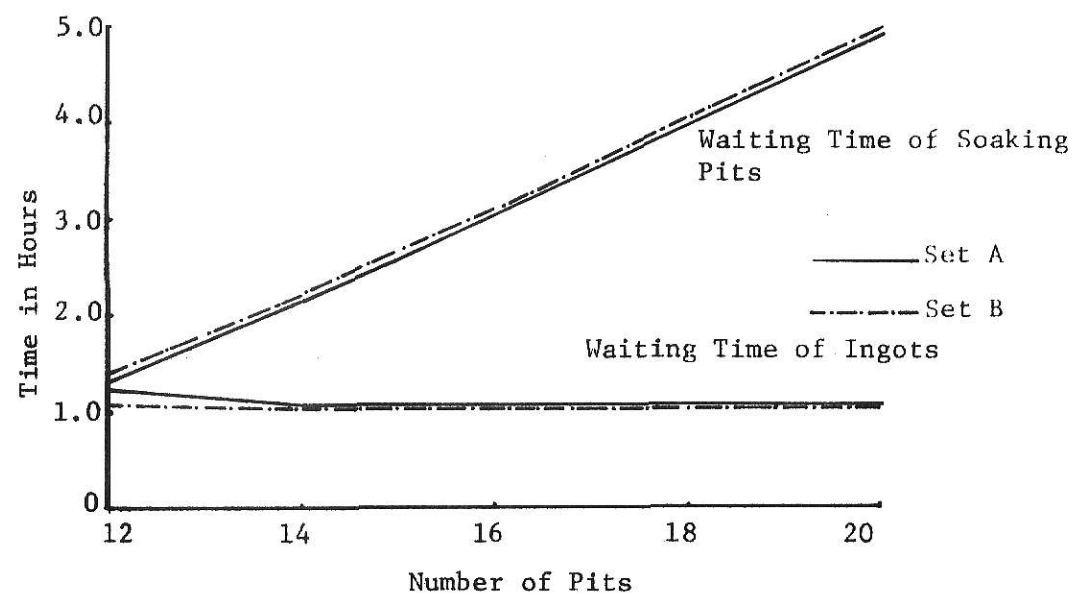

Figure 4.2. Relation Between Waiting Time of Ingots, Soaking Pits and Number of Soaking Pits in Sets A and B.

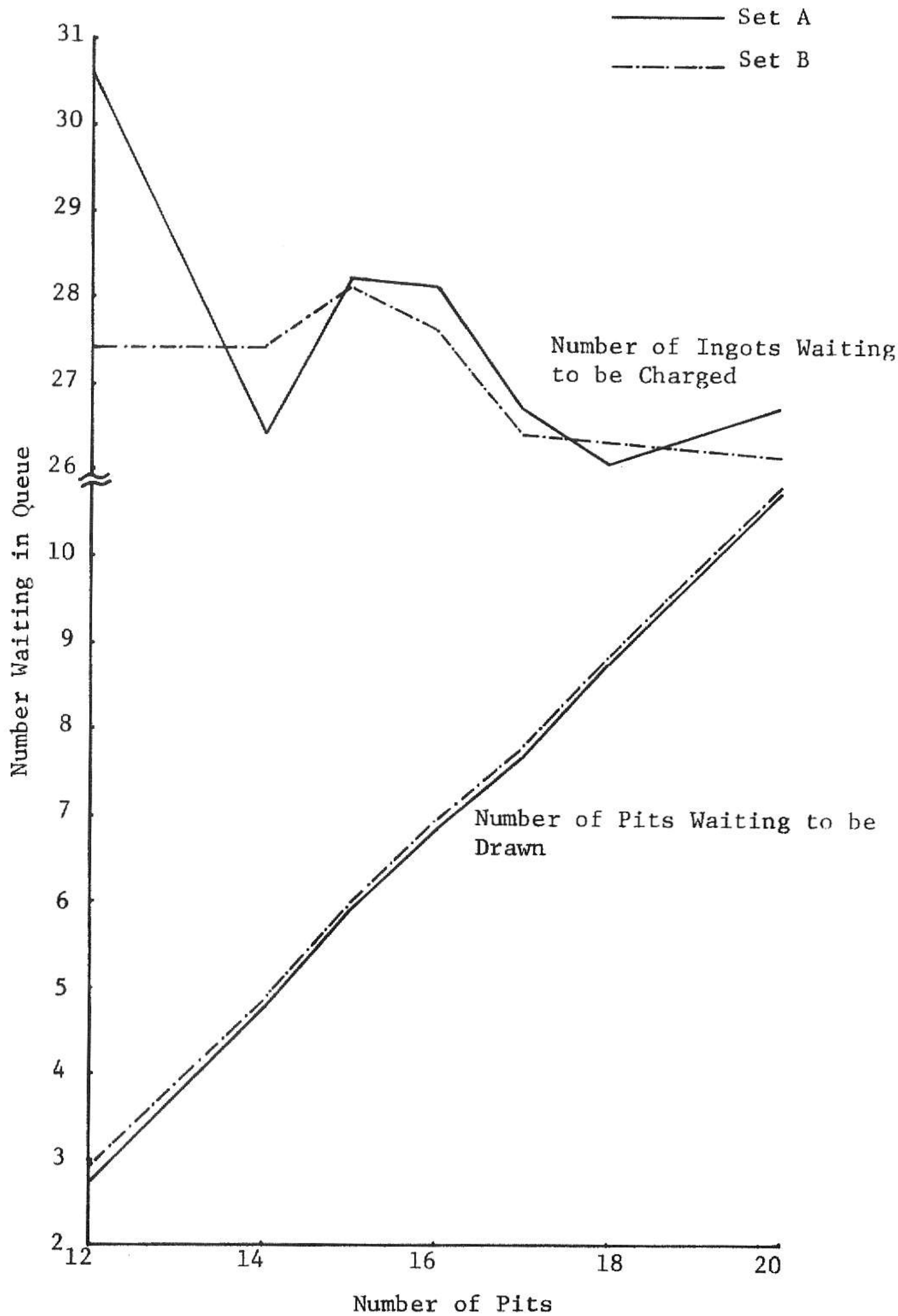

Figure 4.3 Relation Between Ingots, Pits Waiting in Queue and the Number of Soaking Pits in Sets A and B.

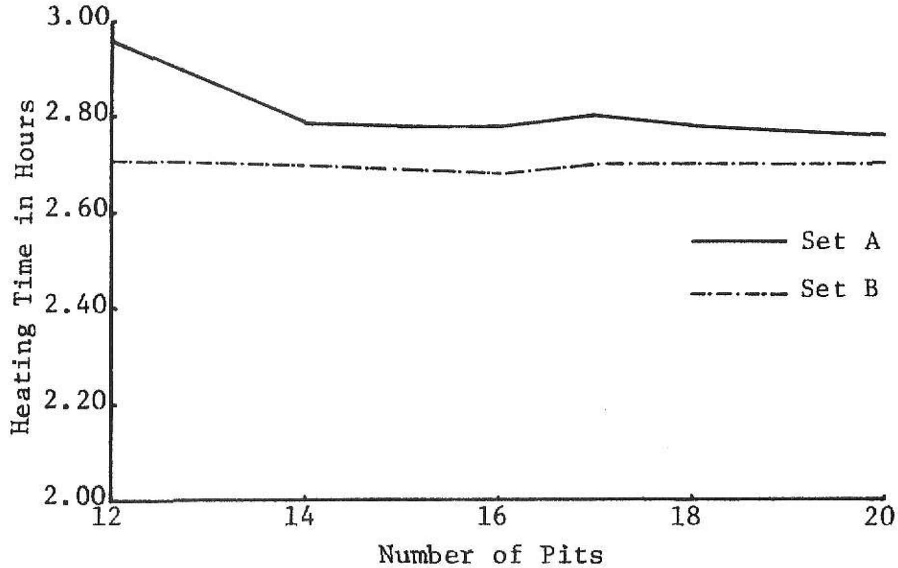

Figure 4.4 Relation Between Ingot Heating Time and Number of Soaking Pits in Sets A and B.

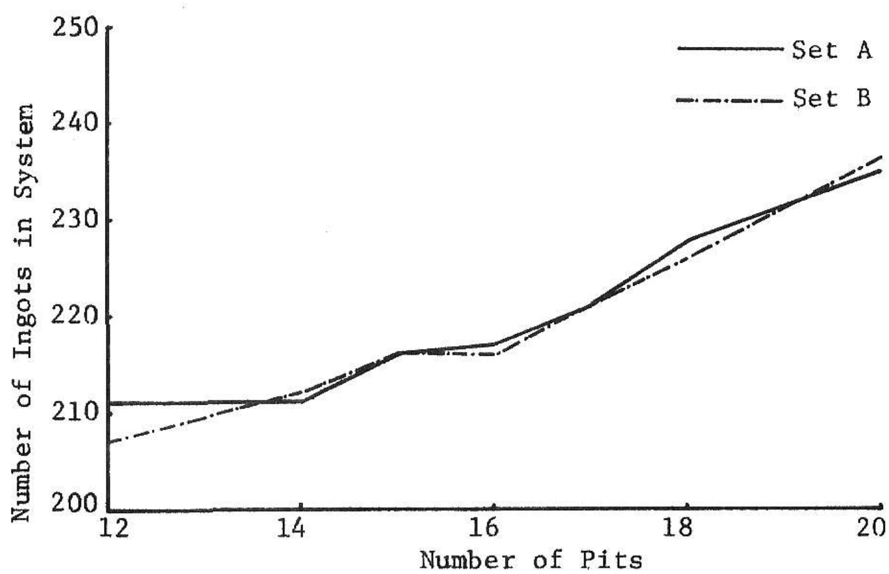

Figure 4.5 Relation Between Number of Ingots and Number of Pits in Sets A and B.

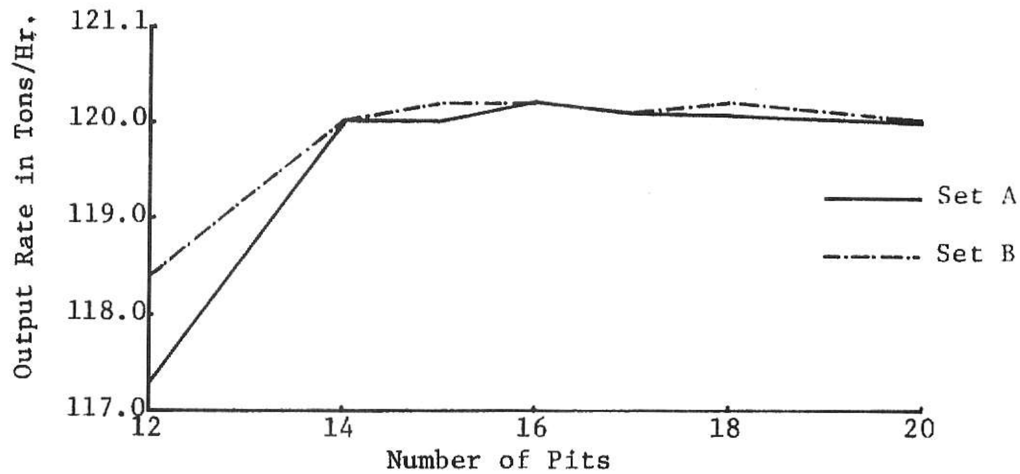

Figure 4.6 Relation Between Output Rate and Number of Pits in Sets A and B.

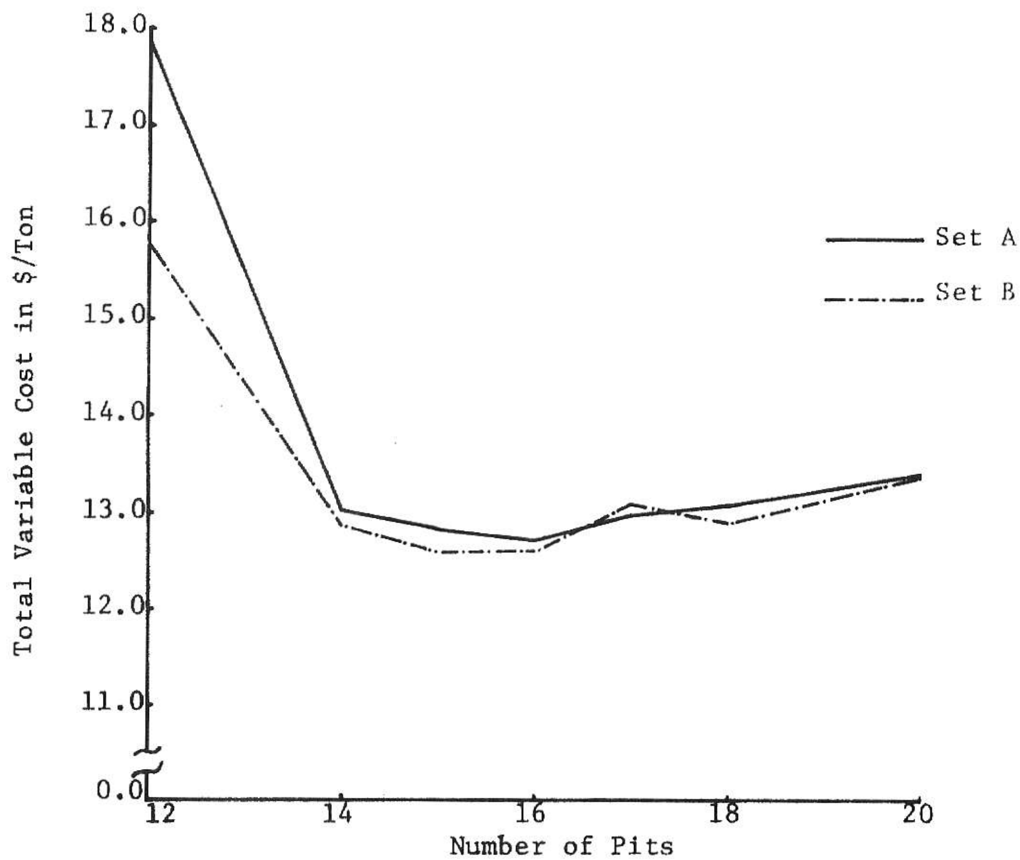

Figure 4.7 Relation Between Total Variable Cost/Ton and Number of Pits in Sets A and B.

1. A crane not being available for drawing owing to mechanical or electrical failure.
2. The blooming mill being inoperative for similar reasons.
3. No soaked ingots being available for drawing.

The analytical model, however, deals only with the third contingency mentioned above. The total fractional mill downtime owing to the first two factors can be calculated with the help of set algebra and the data provided in Tables 3.2 and 3.3. The resulting 'unavoidable' mill downtime is given in Table 4.3. These values added to the calculated probability of 'no hot steel' for varying number of pits according to the laws of set algebra give the total fractional mill downtime analytically. The same table also lists the fractional 1^{o}st time owing to all three factors, obtained during the simulation runs for Set A. Figure 4.8 shows plots of the theoretical and simulated values with increasing number of pits. The theoretical values form an exponential curve that is asymptotic to the line parallel to the x-axis representing mill idling due to crane and/or mill breakdowns. The simulated curve is a more optimistic curve and is expected to be asymptotic to the same line. That this curve goes below the asymptote at all could mean the precision of the simulation model can be further improved upon.

The results for Sets C and D shown in Figures 4.9 through 4.15 will now be discussed with particular emphasis on those aspects where these sets differ from Sets A and B. In Sets C and D, the interarrival times as well as the crane and mill breakdown durations all have Erlang 4 type

Table 4.3 Comparison of Analytical and Simulation Results in Set A

No. of pits	Calculated probability of 'no hot steel'	Fraction of run time lost due to other reasons	Total fractional lost time calculated analytically	Total fractional lost time during simulation run
12	0.05537	0.0465	0.10187	0.0650
13	0.03350	0.0465	0.08000	
14	0.01910	0.0465	0.06560	0.0454
15	0.01026	0.0465	0.05676	0.0453
16	0.00519	0.0465	0.05169	0.0436
17	0.00248	0.0465	0.04898	0.0443
18	0.00112	0.0465	0.04762	0.0446
19	0.00048	0.0465	0.04698	
20	0.00019	0.0465	0.04669	0.0452

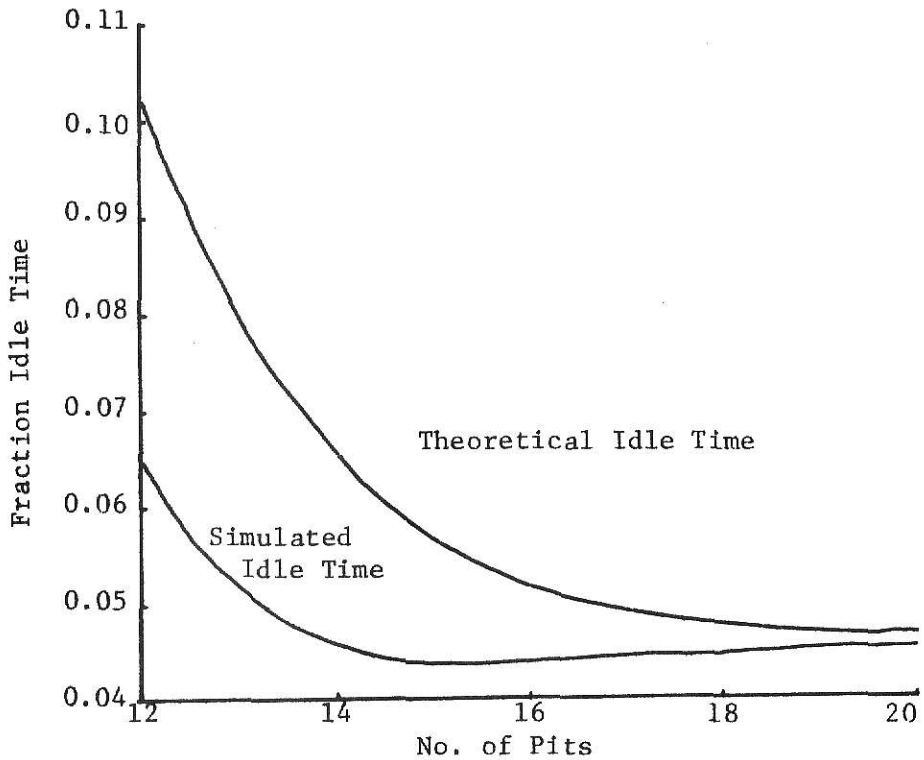

Figure 4.8 Fractional Idle Time of Mills (Analytical and Simulation Values) Versus Number of Pits in Set A

distribution instead of the exponential distribution used in the earlier Sets. However, the remaining parameters for the distributions are the same as before, in both Sets C and D. The resulting distribution curves pass through the origin and are more skewed to the right than the exponential curve. A readily discernable effect of this is the vastly reduced intake of 'hot' ingots into the system. Whereas cold ingots from the bank constituted a mere twenty two percent of the input into the system in Sets A and B, this value rose fifty four percent in Sets C and D. A natural corollary to an increased intake of cold ingots is the increased value of the average heating time of all ingots, (Column 9 of Table 4.2) and a corresponding increase in the fuel cost (Column 14) for both Sets C and D. The increased transient time (heating time) of the pits would naturally result in a smaller number of pits waiting to be drawn. Comparing Figures 4.3 and 4.11, it is apparent that for the first two Sets with twenty pits in the system, the mean number of pits waiting to be drawn is about 10.75, see Column 7 of Table 4.2. The same value for Sets C and D is 8.95. These figures indicate that in the latter two sets, the mean number of ingots in queue has decreased by almost fifty percent.

Crane utilization for all sets remains roughly at about the same level, Figure 4.9. The output rate for Sets C and D has decreased by about five percent which probably contributes heavily to the almost hundred percent increase in the downtime cost per ton, see Columns 13, 17 of Table 4.2 and Figure 4.14. Other factors contributing to the increased downtime cost would be the longer durations of mill and crane

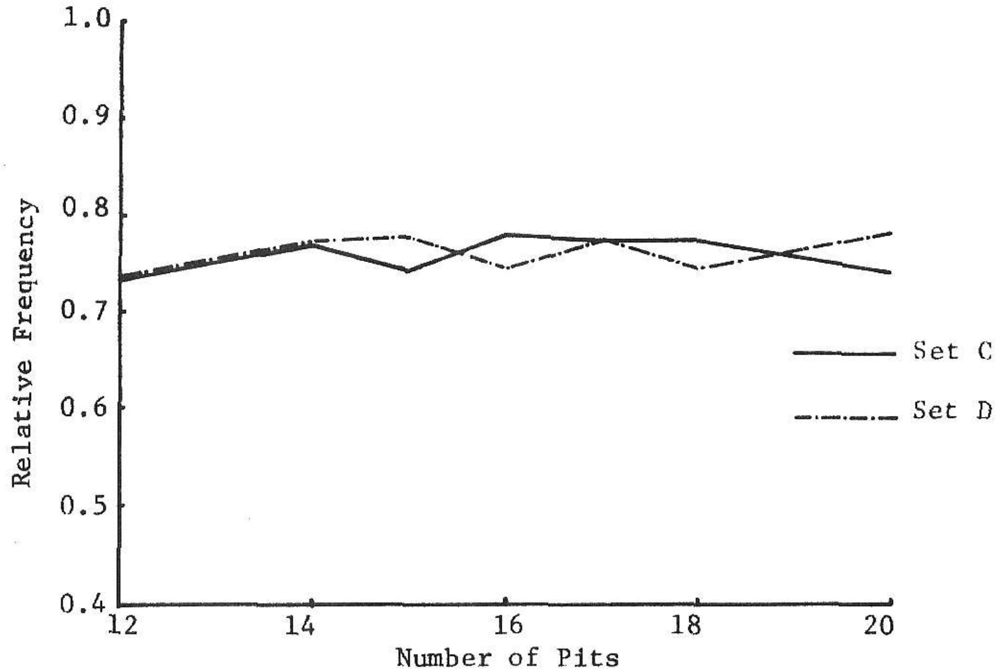

Figure 4.9 Relation Between Crane Utilization and Number of Pits in Sets C and D.

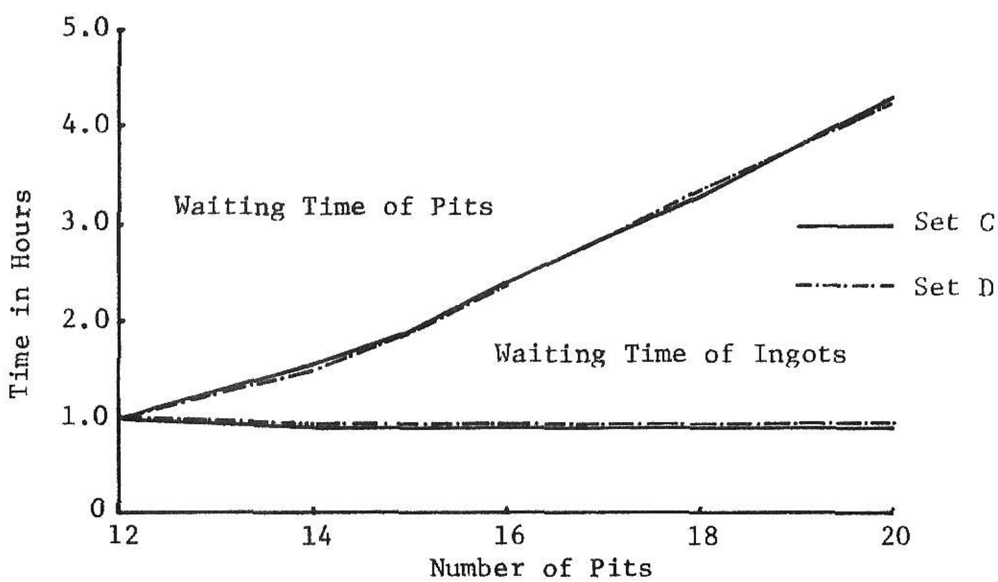

Figure 4.10 Relation Between Waiting Time of Ingots, Soaking Pits and Number of Pits in Sets C and D.

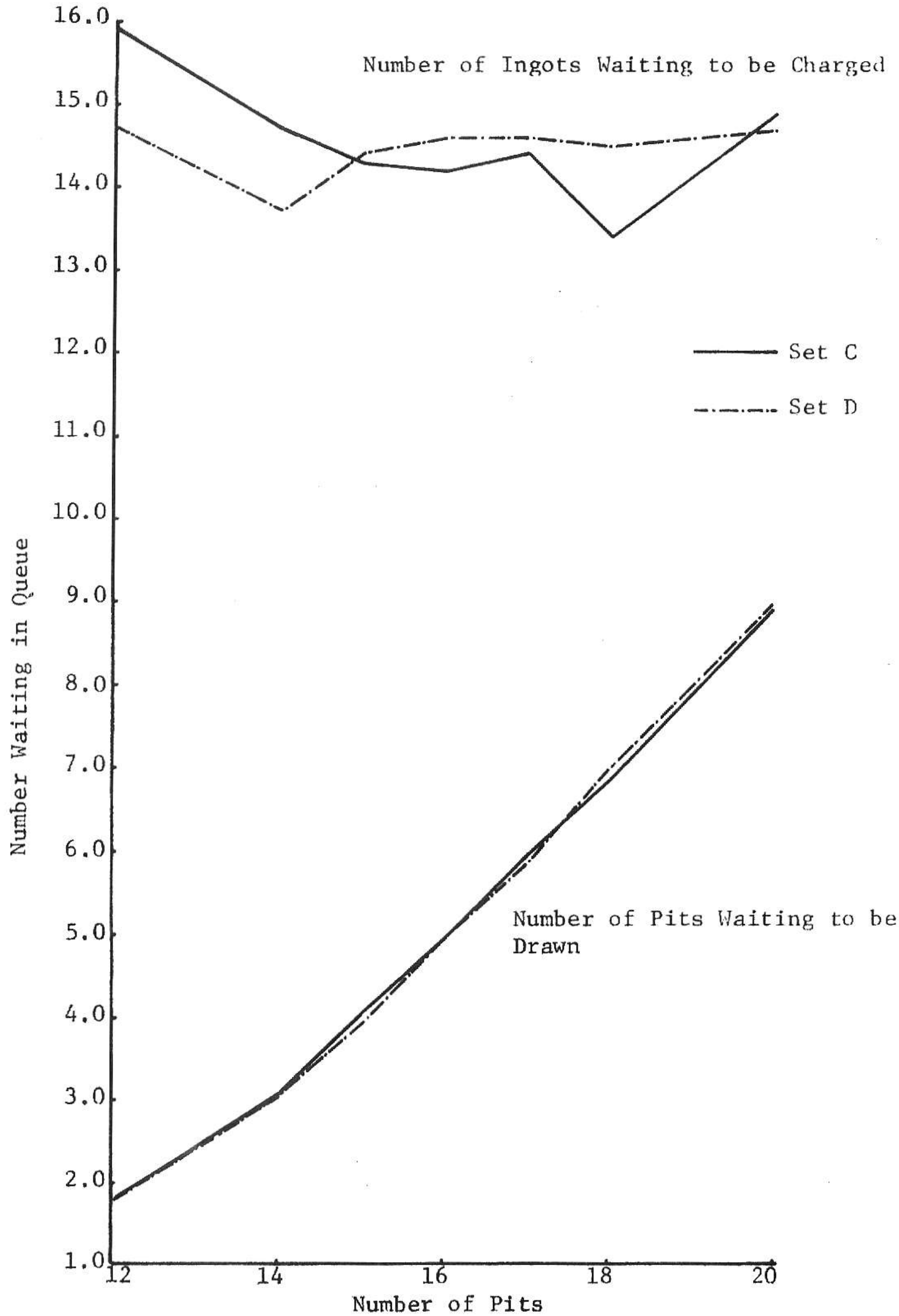

Figure 4.11 Relation Between Ingots, Pits Waiting in Queue and Number of Pits in Sets C and D

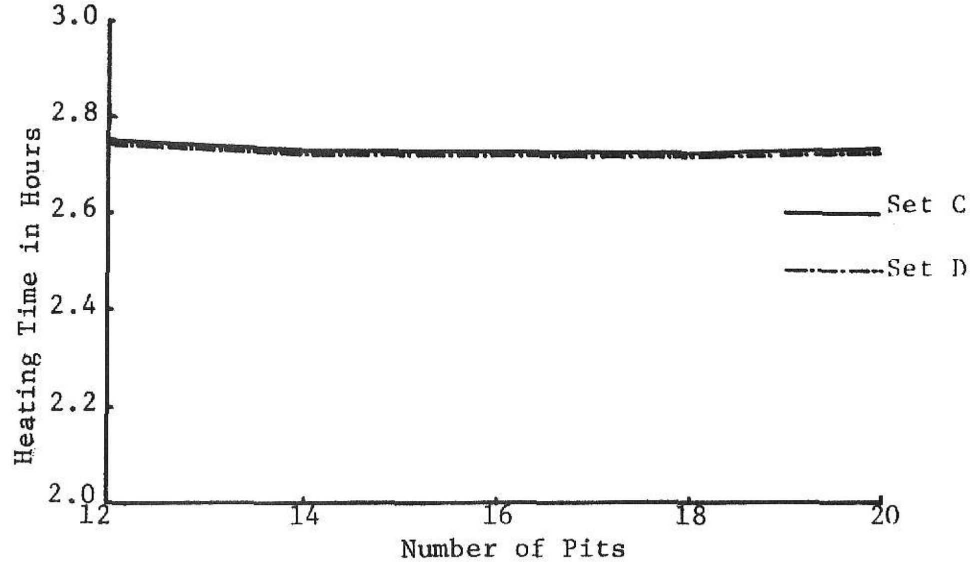

Figure 4.12 Relation Between Ingot Heating Time and Number of Soaking Pits in Sets C and D

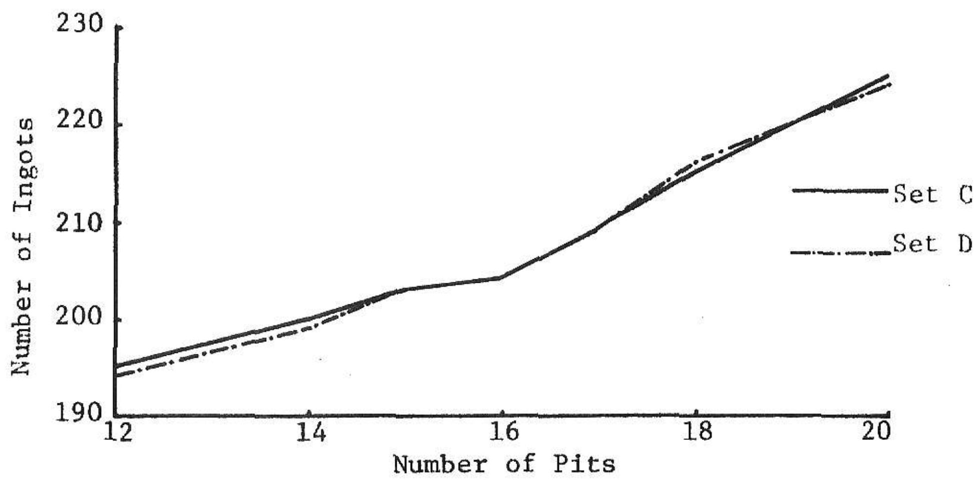

Figure 4.13 Relation Between Number of Ingots in System and Number of Pits in Sets C and D

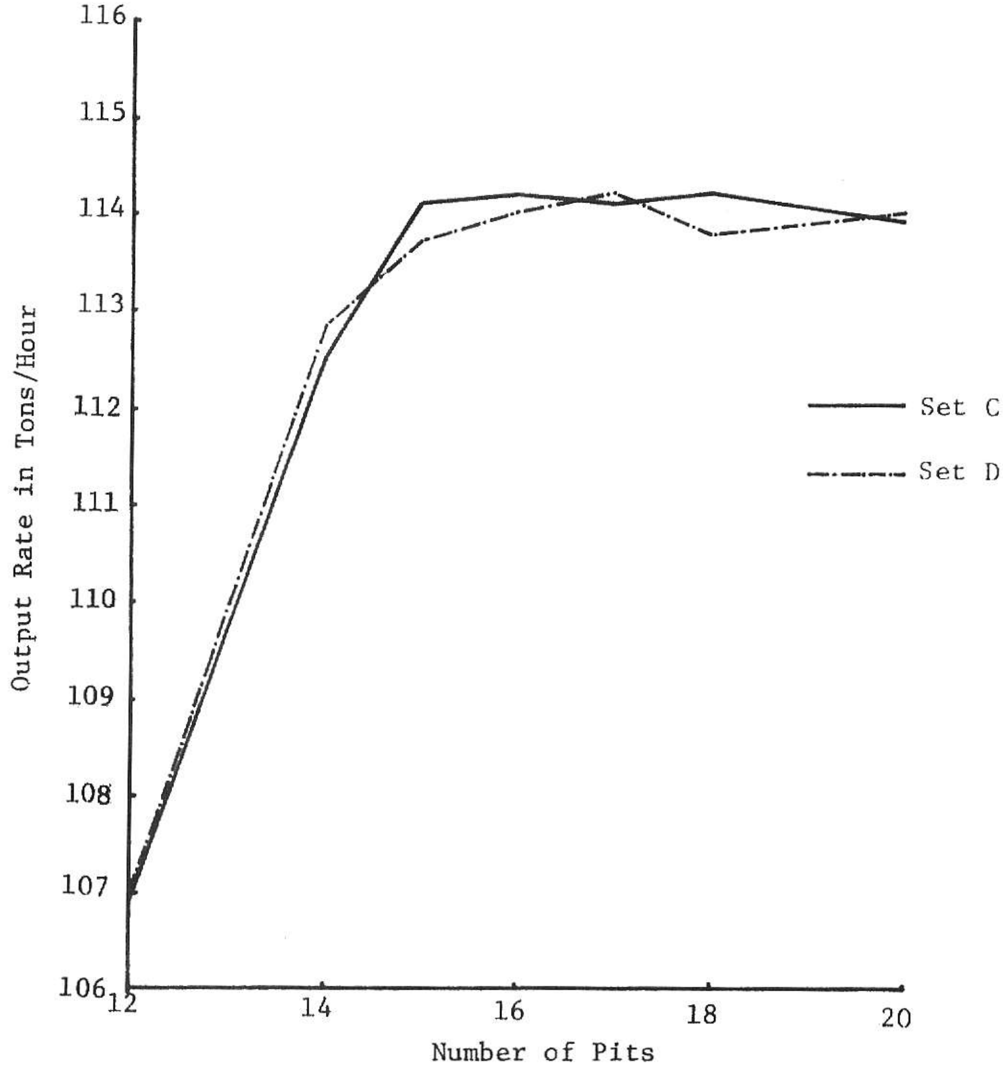

Figure 4.14 Relation Between Output Rate and Number of Pits in Sets C and D

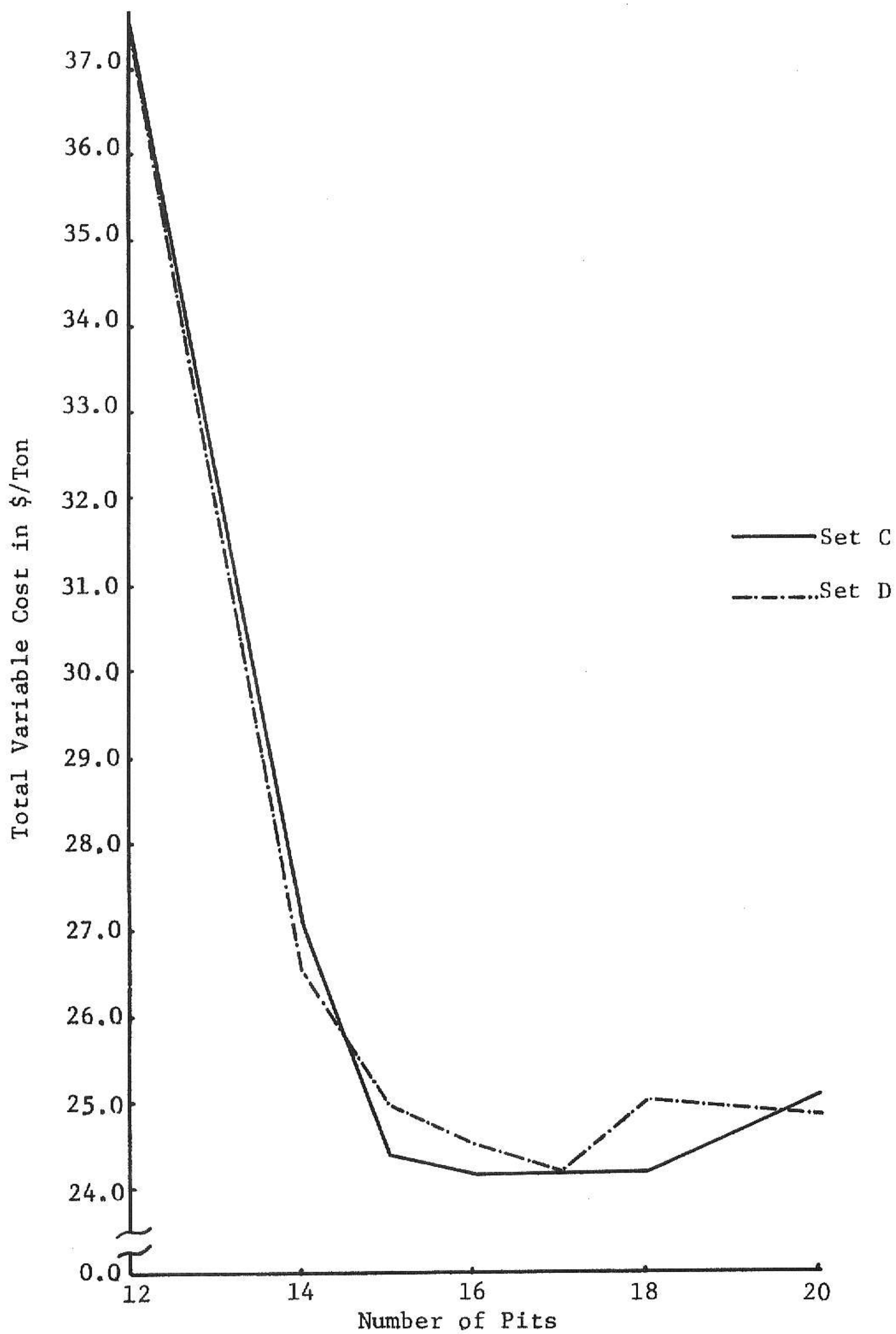

Figure 4.15 Relation Between Total Variable Cost/Ton and Number of Pits in Sets C and D.

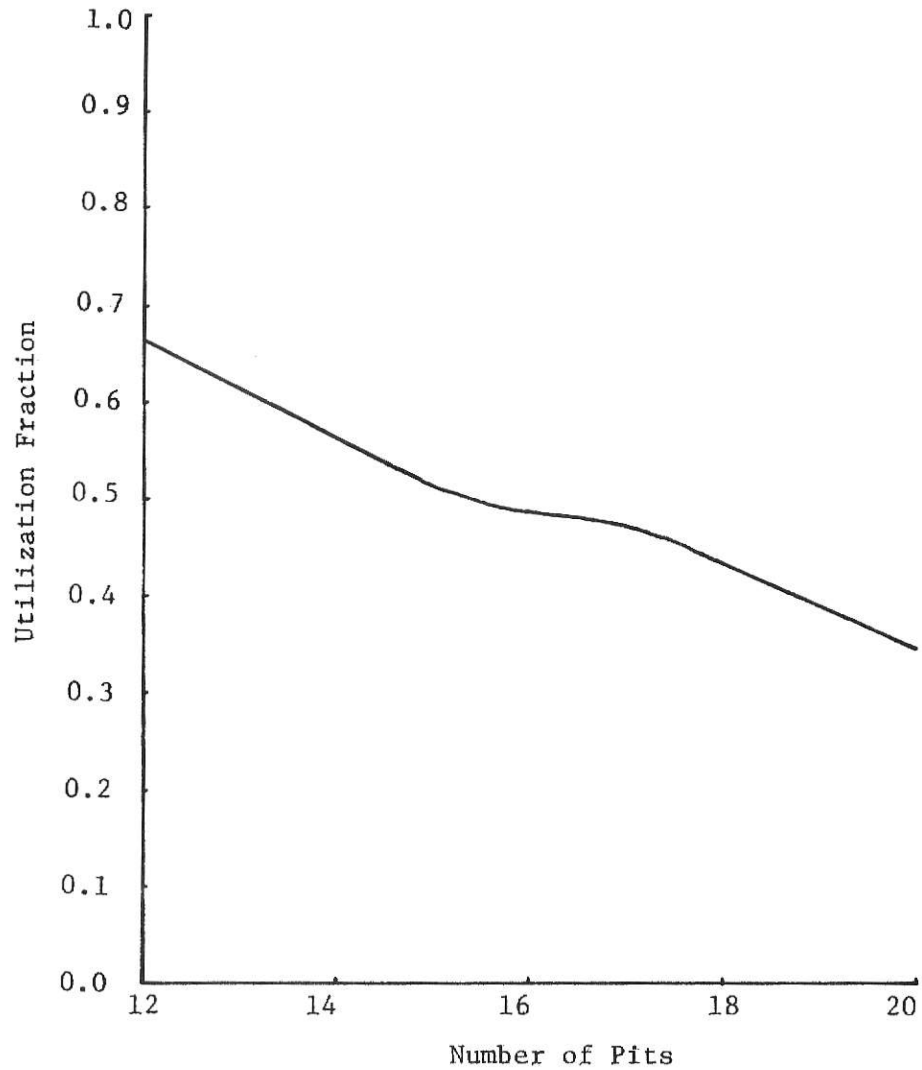

Figure 4.16 Relation Between Pit Utilization and Number of Pits for Set A.

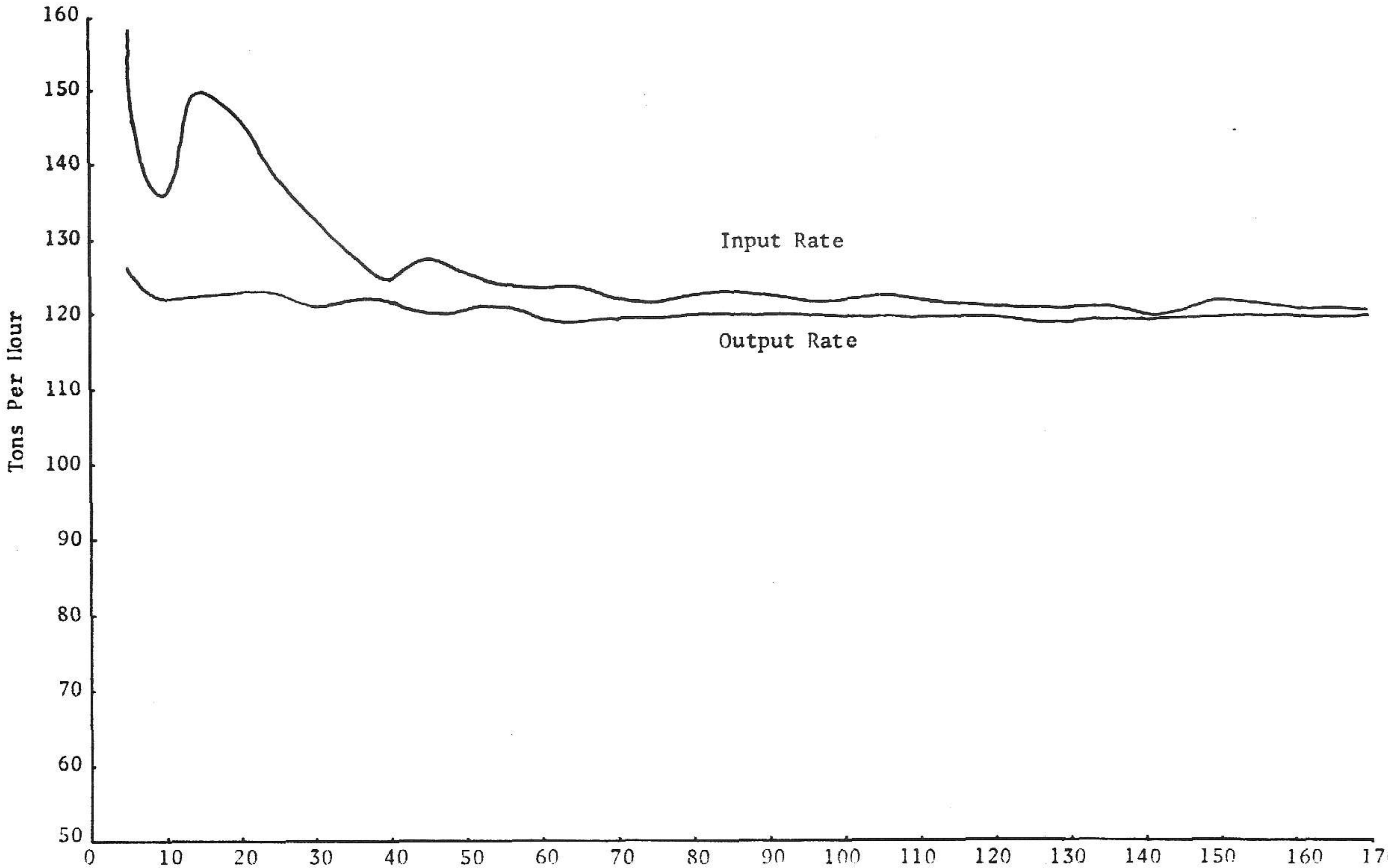

Figure 4.17. Input and Output Rates Approaching Equilibrium: Set A

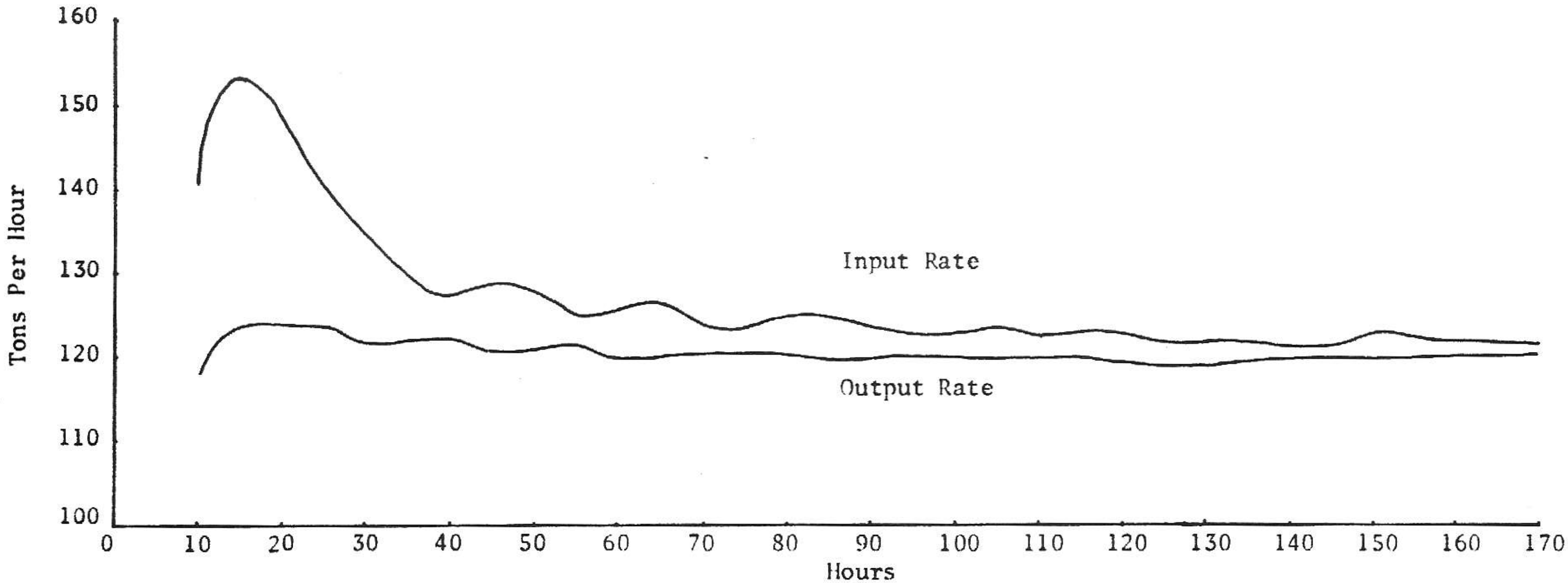

Figure 4.18. Input and Output Rates Approaching Equilibrium; Set B

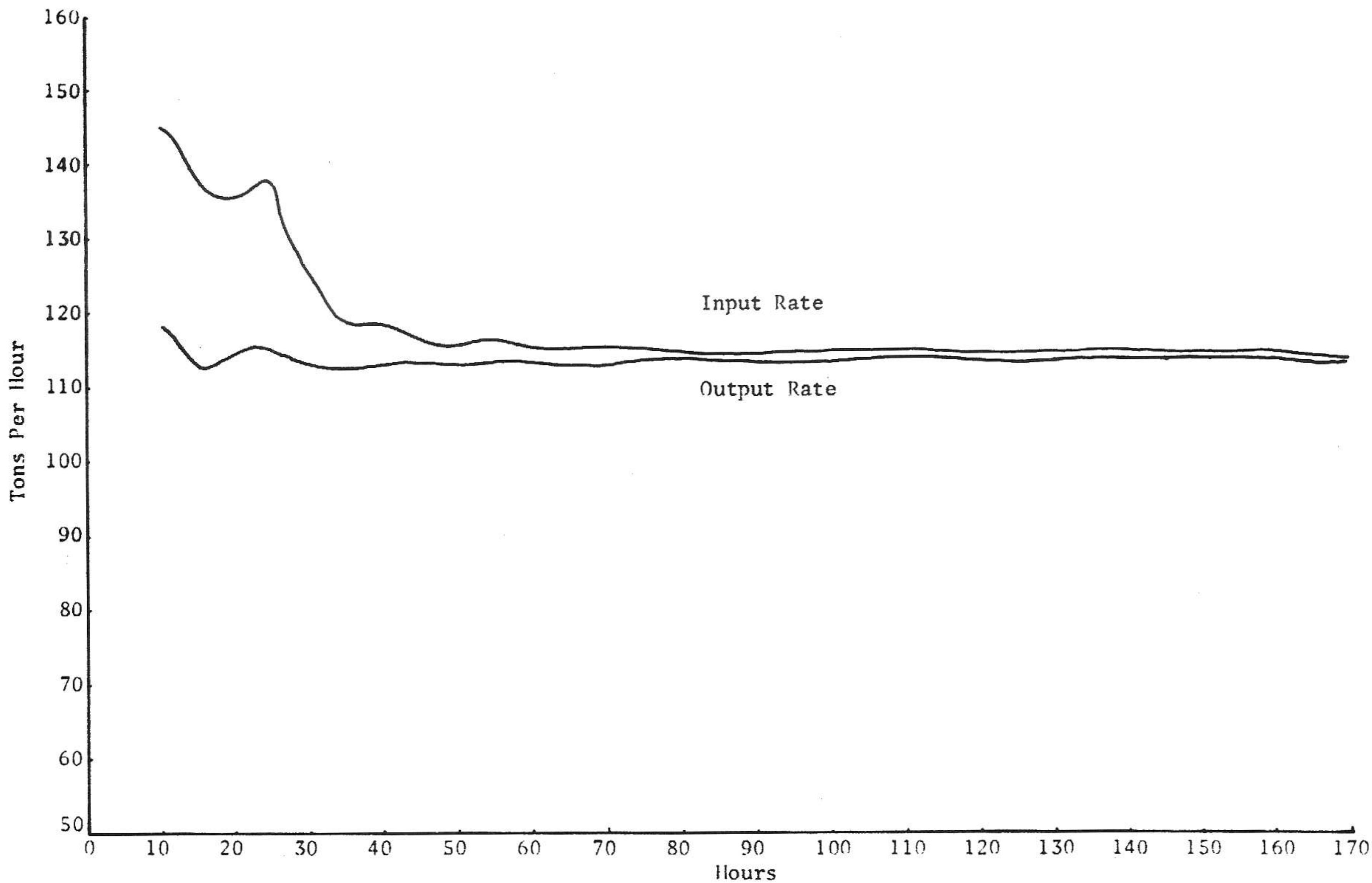

Figure 4.19. Input and Output Rates Approaching Equilibrium; Set C

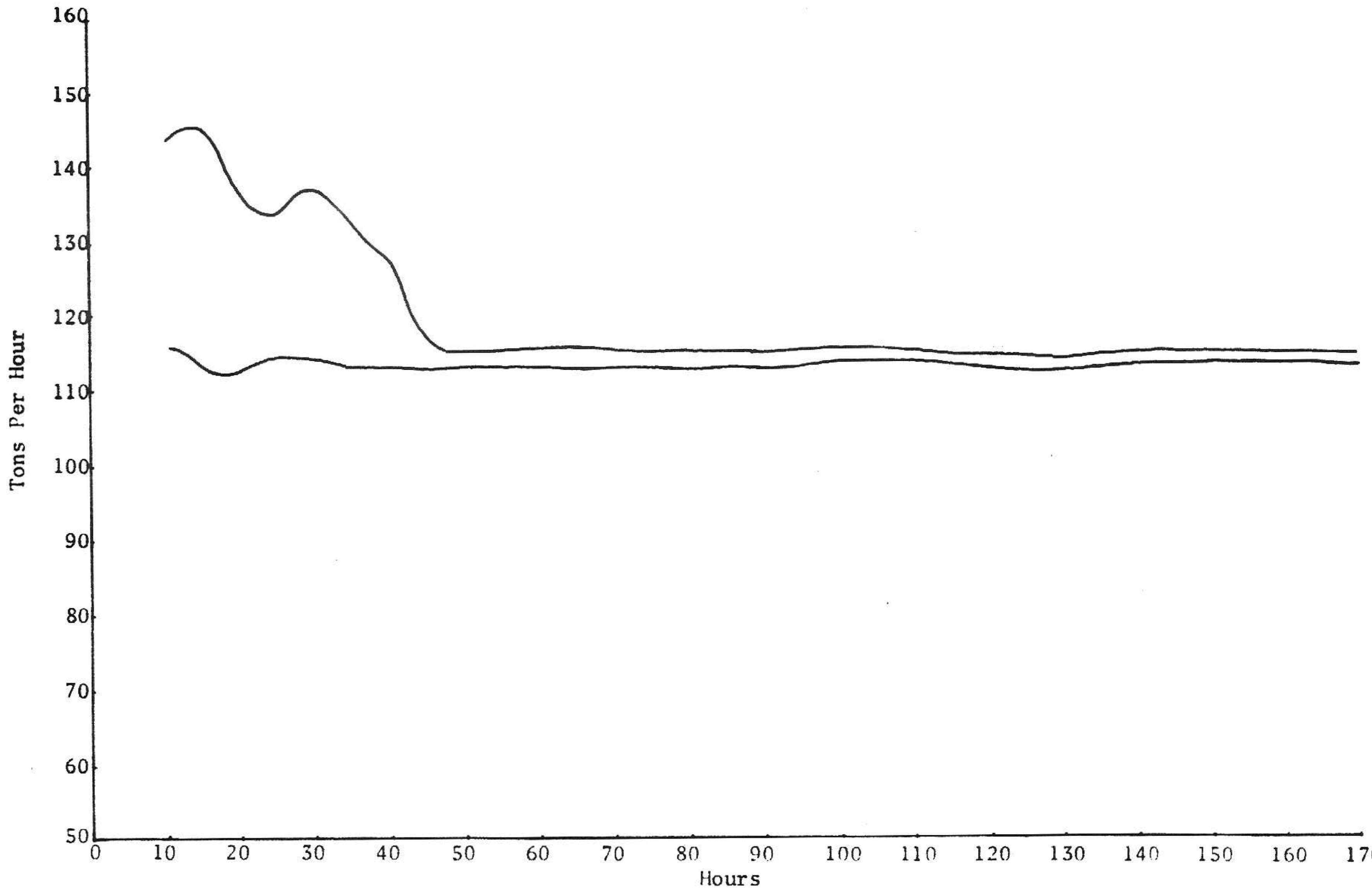

Figure 4.20. Input and Output Rates Approaching Equilibrium; Set D

downtime owing to the shape of the Erlang 4 distribution curve. Both capital and maintenance costs are a little greater than in Sets A and B because of lower output rates. The penalty for not having sufficient reheating capacity is much greater, as a percentage of the minimum cost per ton, for Sets C and D. The minimum numbers of pits for Sets C and D are at sixteen and seventeen, respectively.

CHAPTER V

SUMMARY AND CONCLUSIONS

Steel is the backbone of industrialization and operations research techniques can be profitably applied to integrated iron and steel plants. The current trend is towards a high degree of automation to reduce the cost of finished steel. For purposes of analysis a steel plant may be divided into (1) the 'productive' units such as the blast furnaces, steelworks and rolling mills; and (2) the 'non-productive' units such as the molten metal mixer and the soaking pit complex. The latter are often neglected by operations researchers. Yet, these are the very areas in which cost reductions can be effected, or alternately, a neglect in these areas could lead to avoidable delays in the productive units.

Figure 1.1 is a process flowchart of an integrated iron and steel plant. The mixer which is an intermediary unit between blast furnaces and steelworks, has metallurgical as well as logistical uses. The soaking pits (hereafter referred to as pits) reheat the ingots produced by the steelworks to the required degree of plasticity before they are processed by the blooming mill. In addition, the pits reheat cold ingots stored in an ingot bank. These cold ingots comprise an excess of production by the steelworks and/or special purpose ingots imported. The layout of a typical pit-mill complex is depicted in Figure 1.2.

The capacities of the mixers have to be carefully calculated taking into account future expansions, if starvation of the steel furnaces is to be avoided. The reheating capacity of the soaking pits, likewise, has to be carefully optimized and that is the problem dealt with by this investigation.

The soaking pit area can become a bottleneck if the various components are not carefully designed. There must be ample trackage making the pits highly accessible and the tracks must avoid crossing each other as much as possible. Often there is an attempt to economize on capital intensive soaking pit facilities. Sometimes the mean output rate from these pits may match or even exceed the mean rolling rate of the blooming mill; but unless the stochastic nature of the ingot reheating process is accounted for, there could be spells of mill starvation. The seriousness of this condition can be comprehended, if it is realized that the blooming mill, by virture of the limited amount of productive time available per year, constitutes an upper limit to production. Increased mill downtime would result in decreased output and loss of customers. In addition, the cost of mill idle time and other connected units and labor as well as overheads would have to be absorbed by this decreased production thereby increasing the price of finished steel.

Though the objectives of the several authors in this field are diverse, the basic aim has been to increase the efficiency at some point or the other. Brancher, Stringer and Savage [4] have brought about substantial reduction in tracktime by a judicious application of the critical path method. A similar end has been achieved by Hindson and Sibakin [9] with greater attention paid to the correlation of mill drafts with the ingot temperatures and the number of passes required. The general consensus among the above authors seems to be that a more thorough knowledge of ingot heat transfer phenomena could lead to further economies in soaking pit practice. The mathematical approach proposed by Kung, Dahm and DeLancey [10] seems to fill this need but is cumbersome to use. The cyclic queueing approach proposed by Posner and Bernholtz, in arriving at an expression for the probability of the mill being idle for want of hot steel, is the most promising yet because of the simplicity of the final expression. However, the question of its validity remains, since it does not consider several factors, such as the interactions between the cranes, pits and mill, which affect the operating characteristics of the system.

So far, it has been recognized that the process of reheating of ingots would cause expensive mill idling if due attention is not given. On the one hand, the reheating facilities could be expanded with a corresponding increase in the cost of this service. On the other hand, savings could be effected by decreasing the waiting time of the ingots as well as the idling time of the mills. The optimal reheating capacity would be the breakeven point for decreasing and increasing costs. The objective of this study is to find an economic basis for optimizing on the reheating capacity of the soaking pits.

5.1 Statement of the Problem

The system as investigated consists of the pit area with the auxilliaries. Four steel manufacturing furnaces supplying freshly cast 'hot' ingots and an ingot bank for 'cold' ingots form the boundary of the system on the input side, and the blooming mill on the output side. A series of soaking pits installed in a row is placed in a building adjacent to the blooming mill. Two overhead traveling cranes spanning the pit area and all the tracks charge incoming ingots (hot and cold) into the pits and when a pit is ready to be drawn, the ingots are removed, one by one, onto the ingot chariot. The ingot chariot plying between the pit being drawn and the mill table conveys the soaked ingots one at a time to the mill, keeping pace with the mill rolling rate.

The following objectives are to be aimed at in the design and operation of a modern soaking pit: (1) Total metallurgical control over the ingots being reheated; (2) Minimum capital expenditure and maintenance cost; and (3) Compactness and ability to keep pace with the mill. No compromise can be made as regards the first objective. The second calls for reduced expenditure and a compromise will have to be reached between the second and the third objectives as the third implies increased expenditure.

The pit area can be represented as a closed cycle with a single service station (blooming mill with an overhead crane) and m units (soaking pits) needing service moving in a cyclic fashion. Each soaking pit holds a certain number of ingots. The service time is the time during which a crane draws all the ingots from a pit and the mill completes processing them. This service time is assumed to have an exponential distribution. Immediately on completion of service, the unit (pit) commences on its 'transit' time. The transit time is the sum of the time taken to recharge the pit with hot or cold ingots and the reheating time. The pit then joins the queue awaiting service, with the maximum queue length being m.

Prior to constructing a simulation model, it must be decided as to which responses need to be studied. Collection of the following statistics and measures of performance should give an insight to the response of the system as a whole with changing number of pits:

1. Mean number of ingots in the system.
2. Mean utilization of cranes and pits.
3. Mean number of ingots waiting to be charged.
4. Mean number of pits waiting to be drawn.
5. Mean waiting time of ingots in queue before being charged.
6. Mean waiting time of pits in queue before being drawn.
7. Mean heating time of ingots.
8. Associated costs involved in the process.

The cost analysis of the system involves the recognition of the factors that contribute towards increasing the cost of finished steel as a result of the ingots passing through the system. Broadly, the factors can be divided into two categories; (1) a fixed cost that does not vary with the reheating capacity, and (2) a variable cost that varies with the reheating capacity. The variable cost which is a function of the varying reheating capacity may be subdivided into; (1) the capital cost of adding a soaking pit with all its auxilliaries; (2) the cost of operating the pit such as labor, fuel and power; (3) the maintenance cost for the pit including the cost of repair materials and labor charges; and (4) the cost of an idle blooming mill.

The sum of these cost factors is the total variable reheating cost. The objective of this study is primarily to find the value of the number of pits for which the total variable cost per ton is a minimum. In addition, the nature of the variation of this cost with changing number of pits will be investigated to study the penalties incurred by not operating with this optimal reheating capacity.

5.2 Development of a Simulation Model

The system boundaries are first demarcated. On the input side the batch arrivals from the four furnaces of the steelworks as well as the maintenance cycle of these furnaces comprise the boundary. Cold ingots from the bank are assumed to be always available at the pit area for charging. On the output side, the blooming mill and its breakdown cycle form the boundary. The entire soaking pit operation forms the body of the system. The ingots, steelworks furnaces, soaking pits, cranes and blooming mill are the entities. Their attributes and activities are listed in Table 3.1. The method of 'discrete - event simulation' has been adopted. The principle events considered in the simulation are:

1. The arrival of a batch load of ingots.
2. The arrival of a furnace overhauling contingency.
3. The end of reheating of a batch of ingots by a pit.
4. The end of drawing and charging a pit by one of the cranes.
5. The earliest time the blooming mill is free after rolling a pitload of ingots.

In addition, the program computes the required measures of performance at specific intervals. When the system has reached a steady state, all statistical arrays are reinitialized as only the steady state results are of interest. At the end of the simulation run, the program prints out all the measures of performance accrued. The entire process is accomplished with the help of 10 user-written and 23 standard GASP-IIA subroutines. Several options have been instituted in the program to simulate a variety of situations (see Appendix C).

The simulation is performed under the following assumptions;

1. All parts of the complex are assumed to be uniformly active around the clock. No allowance shall be made for a decreasing rate of activity during shift changes.

2. The pit maintenance time has not been considered owing to insufficient data.

3. Crane traveling time between pits has not been deemed significant enough to warrant inclusion in the model.

4. The firing rate for a pit waiting to be drawn is 20 percent of the full firing rate. This heat is supplied only to make up for heat losses from the waiting pit.

5. As a policy of preventive maintenance is followed, not more than one furnace is idle at any time. Time allowances are not made for breaking in a newly lined furnace.

6. Only preventive maintenance is performed on the cranes. Thus a crane may be idled only after completing the drawing of a pitload of ingots and recharging the pit. The probability of a breakdown in the course of servicing a pit is low enough to be neglected. This is also the case with the mill.

7. The crane operators are assumed to have full information about the pits' status. They know which of the pits are ready to be drawn and the order in which the pits become ready. Thus the pits can be serviced on a first-come, first-served basis.

8. A pit cannot hold more than 16 ingots.

9. No allowance is made for the time taken to strip the arrived ingots. This is presumed to be included in the constant of the heating time formula.

A linear relation of the form $y = mx + c$ is used to compute the heating time of the pitloads of ingots, where y is the heating time, x the track time and m is a constant. The values of m and c depend on several variables such as the shape and size of ingots, the rate of firing, the ambient temperature, and the type of rolled products, and composition of steel. Considering the constraints in this particular simulation, the expression becomes

$$y = 1.06 \text{ (track time)} + 1.75$$

Figure 3.3 shows the relation between the track time and the heating time.

5.3 Experimental Investigation

This investigation comprises four sets of experiments. In each set several experiments have been run in the region of the minimum by changing only the number of pits in each experiment. Sets A and B have the same parameters for the system except that the service discipline for arriving ingots is FCFS in Set A and LCFS in Set B. These two sets, however, differ from the Sets C and D in the arrival, mill and crane breakdown distributions. Furthermore a comparison has been made between the results obtained from Set A and the analytical results.

The important factors (independent variables) used in the simulation are listed in Table 4.1 for each of the four sets. Strictly speaking, any factor that is randomly distributed, is said to be uncontrolled. However, a degree of control has been instituted by specifying historic data as parametric values. The distribution for interarrival times of ingot batches as well as those for mill and crane breakdowns are of this type. Some other factors have been totally controlled because it is desired to study the effect of these particular levels of the factor on the system. The service discipline for ingots, the minimum number of ingots charged to a pit, and the service discipline for pits waiting to be drawn are totally controlled. Except for the number of pits in each experiment, all factors in the system are qualitative as they merely serve to increase the accuracy of the model.

The determination of the onset of steady state for experimental runs has been done on the basis of an equilibrium being reached between the rate of ingots entering the system and the rate leaving it. Pilot runs made for each of the four sets indicate that this equilibrium is generally reached after 50 to 60 hours have passed on the simulation clock. However, the prime response, namely, the total variable cost per ton, does not stabilize sufficiently for about a thousand hours. Since the initial conditions for the system for all the experiments have been kept identical, it has been conservatively assumed that steady state for all experiments would have been well established by the time a hundred hours have elapsed on the simulation dock. Thus, resetting has been done at a hundred hours for all experiments. The length of each experiment has likewise been decided after observing the fluctuation of the prime response. A period of 1500 hours on the simulation clock has been deemed sufficient on a trial-and-error basis. All statistics collected are cumulative and random errors can be further eliminated by increasing the run time. The various seed values for the generation of random numbers have been kept identical in all the experiments, not only to help predetermine the time it takes to reach the steady state, but also to sharpen the contrast between computer runs.

In each set, the minimum number of soaking pits has been assumed to exist between twelve and twenty. A sequential search has been conducted first, followed by an exhaustive search in the vicinity of the minimum. This procedure has resulted in seven experiments being run in each set, twenty-eight in all.

5.4 Analysis of Results

Considering Sets A and B, it is seen that the total cost curves for both sets have the expected unimodal shape, see Figure 4.7. The curves converge near the minimum and thereafter, run very close to each other. Thus the service discipline matters only when there are less than the optimal number of pits. The initial slope indicates that the cost of heating rises steeply if the number of pits in the system is reduced below the optimal number. At the optimal value of sixteen pits for Set A and fifteen pits for Set B, the total variable costs are practically equal, indicating that the service discipline does not play an important role in reducing the minimum cost per ton or shifting the minimum point. The almost flat region near the minimum and to its right indicates that the decision to operate with a certain number of pits is not critical provided the minima is kept as a lower limit.

If the possibilities of pit failures and relining are considered, it is expected that the result would have only been a shift of the minimum point of the curve to the right along the x-axis by a quantity equal to the number of pits being down on the average. The minimum cost might have been higher than in the present case. Further, as may be seen from Table 4.2, the major influencing factor for the total cost curve is the mill downtime, accounting for more than 85 percent of the total cost while capital, fuel, and maintenance costs contribute the remainder. This fact, though explicit in this table, does not impress vividly in real life situations where management would yet balk from spending about $400,000 on a single soaking pit.

Crane utilization appears to be fairly constant in both Sets A and B at all levels of the prime factor as Figure 4.1 depicts. How much of the mill idle time has been due to non-availability of cranes is a question that remains to be answered. Experiments conducted with crane operation rules, other than the ones used in this model, may shed some light on that aspect. The number of soaking pits waiting to be drawn increases linearly at the rate of almost an additional pit inqueue for an increase of one pit in the system, see Figure 4.3. Also, the waiting time of pits increases linearly at the rate of almost an additional hour for an increase of two pits in the system within the range of the investigation. One would expect that the fuel cost would accordingly increase to make up for heat lost while waiting to be drawn. Column 14 of Table 4.2 shows this to be true but not significantly so. However, a portion of this increase would be due to the declining utilization of pits as seen in Figure 4.16.

The waiting time of ingots does not seem to be affected by increasing the number of pits, see Figure 4.2. Production rate increases only till a little before the optimal number of pits is reached and then remains very steady thereafter. This is in keeping with the model characteristics wherein an upper limit to production is inbuilt owing to the mill rate. Thus, after the optimal pit number is passed only marginal decrements occur in mill idle time. In fact, the downtime soon begins to increase. At this stage an anomolous situation is faced because it is reasonable to expect that the mill idle time would decrease monotonically with an increase in the number of pits. The reason for this increase is the decreasing utilization of pits with an increase in their number in the system, see Figure 4.16. There is always the probability of some idle-time between the drawing of consecutive pits because a crane or the mill itself may need repair and in-process breakdowns have been excluded from the model. If processing a pitload of ingots is considered as a 'transaction', then it follows that with an increase in the number of transactions, mill idling probabilities increase after a minimum is reached.

A comparison between results obtained from the analytical method introduced in Chapter II and the simulation results for Set A is of interest. The analytical model considers mill idling only due to the non-availability of soaked ingots. A constant calculated from historical data in Tables 3.2 and 3.3 according to the laws of set algebra represents mill idle time due to mill and crane failures. This constant could be added to give the total mill downtime, see Table 4.3. Figure 4.8 depicts the theoretical curve to be asymptotic to the line parallel to the X-axis representing this constant value. The downtime curve obtained from simulation results has roughly the same shape but represents significantly more 'optimistic' values. That this curve goes below the calculated asymptote at all could mean that the accuracy of the simulation program could be further improved upon.

The results for Sets C and D are much the same as the first two sets with a few differences. The minimum number of pits are at sixteen and seventeen, respectively. The Erlang 4 type distribution used for generating interarrival times and crane and mill breakdown durations, causes a vastly reduced intake of hot ingots into the system. The intake of cold ingots is thereby increased from about 22 percent for Sets A and B to about 54 percent for Sets C and D. Consequently, the average heating time of the ingots has increased (Column 9 of Table 4.2) along with the fuel cost (Column 14). A natural corollory to increased transient time is the reduced number of pits waiting in queue, see Figure 4.11. The almost hundred percent increase in the total cost curve for Sets C and D may be attributed to the five percent decrease in production as well as the longer durations of crane and mill downtimes owing to the shape of the Erlang 4 curve. There is a proportionate increase in the penalty for insufficient reheating capacity but the nature of the cost curve remains the same as before.

5.5 Conclusions

In the case of the exponential interarrival, crane and mill break-down times, the penalty for having a particular number of pits less than the optimal value is far greater than having a similar number of pits in excess. This is because the cost per ton curve flattens out after the minima is reached. As the idling and overhauling of pits has not been considered, it would be prudent to have one or two more pits than the optimal number arrived at in each set.

If the above mentioned distributions are of the Erlang 4 type, the penalty for less than the optimal is even more promounced.

Other factors remaining constant, the service discipline for charging the ingots may be FCFS or LCFS with very little advantage to be gained by using the one or the other. However, LCFS is better economically if the number of pits in the system is less than the optimal and the distributions are of the type as in Set A.

The factor that largely contributes towards increased total variable cost is the idling of the blooming mill. Any effort towards reducing this idling of the mill would be profitably directed. Even a small re-duction in mill idle time offsets the extra costs incurred by increasing the reheating capacity. In this context, it is profitable to undertake preventive maintenance action on the cranes whenever the blooming mill is idled for change of rolls.

The probability of the mill being idle calculated according to the analytical model is a pessimistic value when compared with the simulation results.

Future Research. It would be interesting to study the economies of having two blooming mills processing the ingots in parallel and/or more than two cranes operating in the soaking pit area. The contingency of the soaking pits needing overhaul might be included in the model after collecting sufficient data on the repair cycle. The computer program has several options incorporated in it and multifactorial experiments may be performed to determine the sensitivity of the responses to changing factor levels.

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APPENDIX A

PROGRAM VARIABLES

This Appendix includes (1) Non-GASP variables that are quantitative factors with the values used in the experiments, and (2) GASP-IIA data card variables and their definition and current values. All Non-GASP variables are described in the listing of the computer program in Appendix C.

Following is a list of Quantitative Factors used in the Computer Program.

NPIT	Number of soaking pits in the experiment.
INDEX	Minimum number of ingots charged to a furnace. (INDEX $\leq$ INGMAX) where INGMAX is the maximum number of ingots chargeable.
ABC	Time it takes to process an ingot by the blooming mill such that ABC = 0.0278 Hours.
BBC	Average time taken to charge an ingot to a pit such that BBC = 0.0150 Hours.
CBC	Maximum heating time for an ingot batch such that CBC = 6.0 Hours.
XMT2,XMT1	Upper and lower limits for the number of heats a furnace puts out before going in for relining such that XMT2 = 21.0, and XMT1 = 10.0.
XWT	Net recovery weight for an ingot such that XWT = 3.5 Tons.
XHRS	Maximum available working hours in a year such that XHRS = 8000.0 Hours.
BDNMIL	Fraction of time the mill is not functioning from past data such that BDNMIL = 0.044.

BDNCRN	Fraction of time the crane is not functioning from past data such that BDNCRN = 0.051.
PCOST	Capital cost of a pit per year such that PCOST = $31666.66.
FCOST	Fuel cost in dollars per pit per hour of operation at high fire such that FCOST = $7.87.
BLMCST	Blooming Mill downtime cost per hour such that BLMCST = $671.0
OPPCST	Cost of lost opportunity per hour such that OPPCST = $230.0.
XMCST	Maintenance cost per pit per ton of finished steel such that XMCST = $0.39.
NUMBER(I)	Number of ingots in the I-th type of arriving ingot batch (I $\leq$ 4) NUMBER(1) = 27, NUMBER(2) = 28, NUMBER(3) = 41, NUMBER(4) = 42.
CRMAX,CRMIN	Upper and lower limits for crane breakdown durations if optional uniform distribution is used. CRMAX = 0.7, and CRMIN = 0.5.
XMLMAX,XMLMIN	Upper and lower limits for mill breakdown durations if optional uniform distribution is used. XMLMAX = 0.48, and XMLMIN = 0.3.

ARLMAX,ARLMIN Limits for interarrival times if uniform distribution is used.

ARLMAX = 3.5, and ARLMIN = 3.0.

QLMT Queue length limit for arriving ingots (optional).

POWER Exponent value for queue limiting factor (optional).

COEF Co-efficient of track time in the Heating Time Formula such that

COEF = 1.06.

CONST Constant value in the above formula such that

CONST = 1.75.

INGMAX Maximum number of ingots that may be charged to a pit such that

INGMAX = 16.

Following is a list of GASP - II A data card variables and their definition and current values.

Data Card Type 1: FORMAT (6A2, I4, I2, I2, I4, I4)

NAME Programmer's name.

NPROJ Project number.

MON Month number.

NDAY Day number.

NYR Year number.

NRUNS Number of simulation runs to be made.

Data Card Type 2: FORMAT (10I5)

NPRMS	Number of sets of parameters to be used in simulation. NPRMS $\leq$ 20
NHIST	Number of histograms required for this simulation. NHIST $\leq$ 20
NCLCT	Number of variables for which statistics are collected in subroutine COLCT. NCLCT $\leq$ 25
NSTAT	Number of variables for which statistics are collected in subroutine TMST. NSTAT $\leq$ 25.
ID	Number of columns in the filing array NSET.
IM	Maximum number of attributes of a fixed point type associated with any entry of the filing array. IM $\leq$ 7.
NOQ	Number of files contained in the filing array. NOQ $\leq$ 14.
MXC	Largest number of cells to be used in any histogram. MXC $\leq$ 30.
IMM	Maximum number of attributes of a floating point nature associated with any entry of the filing array. IMM $\leq$ 8.

Data Card Type 3: FORMAT (14I5).

If NHIST is greater than zero, the number of cells for each histogram used is initialized from this data card. The GASP variable NCELS(K) is the number of cells in histogram K, not including the end cells. NCELS(K) $\leq$ MXC - 2 always. If no histograms are used in a simulation, this card is not used. In the current program, the following relation holds absolutely.

NPIT = NHIST = NSTAT - 5; NCLCT = 3

The format specification for Data Card Type 3 allows only 14 values per card. One card of this type is required for each 14 histograms or fraction thereof.

Data Card Type 4: FORMAT (14I5).

There are as many values in this card as there are number of files. KRANK (J) is the variable that determines the attribute on which file J is ranked. If KRANK (2) = 3, File 2 is ranked on ATRIB (3).

Data Card Type 5: FORMAT (14I5).

This card reads values for the vector INN. If INN(J) = 1, File J will be serviced on a 'first-in, first-out' basis. If INN(J) = 2, File J will be serviced on a 'first-in last-out' basis. INN values have to be used in conjunction with KRANK values. INN(2) = 1 and KRANK(2) = 3 specifies that file 2 entries with smaller values of ATRIB(3) are serviced earlier. Thus KRANK(1) = 1 and INN(1) = 1 ensures that events are ordered chronologically.

Data Card Type 6: FORMAT (4F10.4).

This card is needed only if parameters are used in the simulation; i.e., NPRMS $\geq$ 1. Parameters are stored in the array PARAM. Normally, PARAM contains parameters of statistical distributions from which samples are to be obtained during the simulation run. There are NPRMS cards of Type 6.

Data Card Type 7: FORMAT (4I6, 2F10.3, I4).

This card is used to initialize control variables that may change from run to run. The variables are:

MSTOP   Method employed to stop simulation.

- 0 End-of-simulation event has been furnished by programmer
- \+ Simulation ends when TNOW $\geq$ TFIN
- \- Simulation run is completed and final reports should be given, if requested.

JCLR   Index to clear statistical array from run to run.

- $\leq$ 0 Accrue data. Do not clear statistical storage areas.
- 1 Clear statistical storage areas.

NORPT   Control for summary report.

- 0 Final GASP summary to be printed.
- 1 No final summary reporting required.

NEP   Starting card number for reading in data for the next simulation run.

TBEG   Beginning time of simulation run, i.e., initial value of TNOW.

TFIN   Ending time of the simulation run only if MSTOP is positive.

NSEED   Number of seed values used in generating sets of random numbers. NSEED $\leq$ 8.

Data Card Type 7A: FORMAT (8I7).

This card is used only if NSEED > 0. Each value forms the seed from which a set of random numbers are generated by FUNCTION DRAND.

Only one card is needed as NSEED $\leq$ 8.

Data Card Type 8: FORMAT (8I10), FORMAT (8F10.4).

This card is used to initialize the filing array and to insert initial entries into it. Each entry into the file needs two cards. The first card contains the file number and the fixed point attributes (JTRIB). The reading in statement is:

READ (NCRDR, 1110) JQ, (JTRIB(JK), JK = 1, IM)

where JQ is the File number. If JQ is negative, the entire filing array is initialized. If JQ is positive, the values of JTRIB are inserted into an entry in File JQ; FORMAT(8I10). Thus the maximum number of fixed point attributes that can be had is 7. The next card to be read in the same cycle of the DO loop contains floating point variables; FORMAT(8F10.4). Thus ATRIB(8) can be the last value. Since GASP requires at least one initial event to start the simulation, at least one entry is read into File 1. A JQ value of zero signals that all initializing entries have been read in. This is the last of the GASP IIA input.

APPENDIX B

COMPUTER PROGRAM FLOWCHARTS

This Appendix includes the detailed flowcharts of the computer program used to simulate the pit-mill complex. Only the user written external subroutines have been included and none of the standard GASP II-A subroutines.

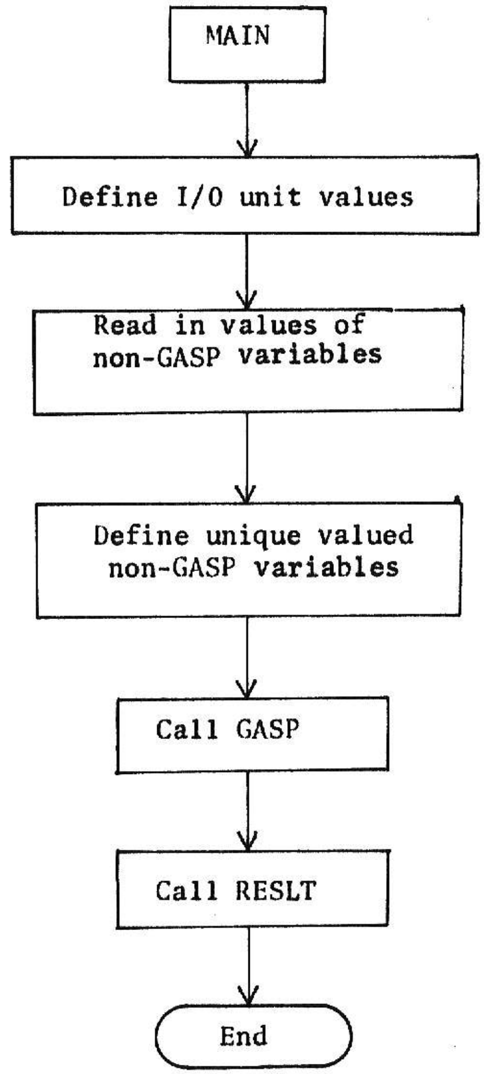

Figure B-1. Main Program

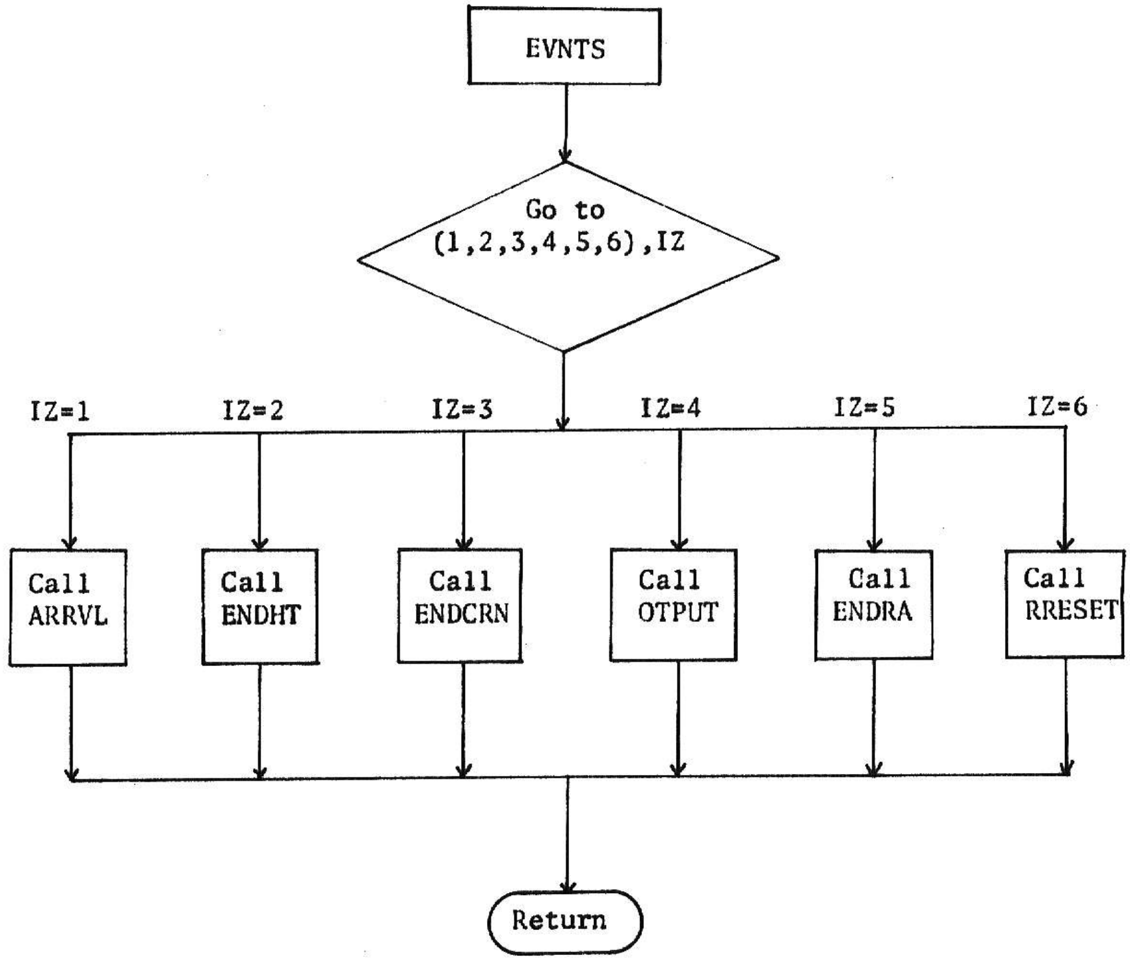

Figure B-2. Subroutine EVNTS

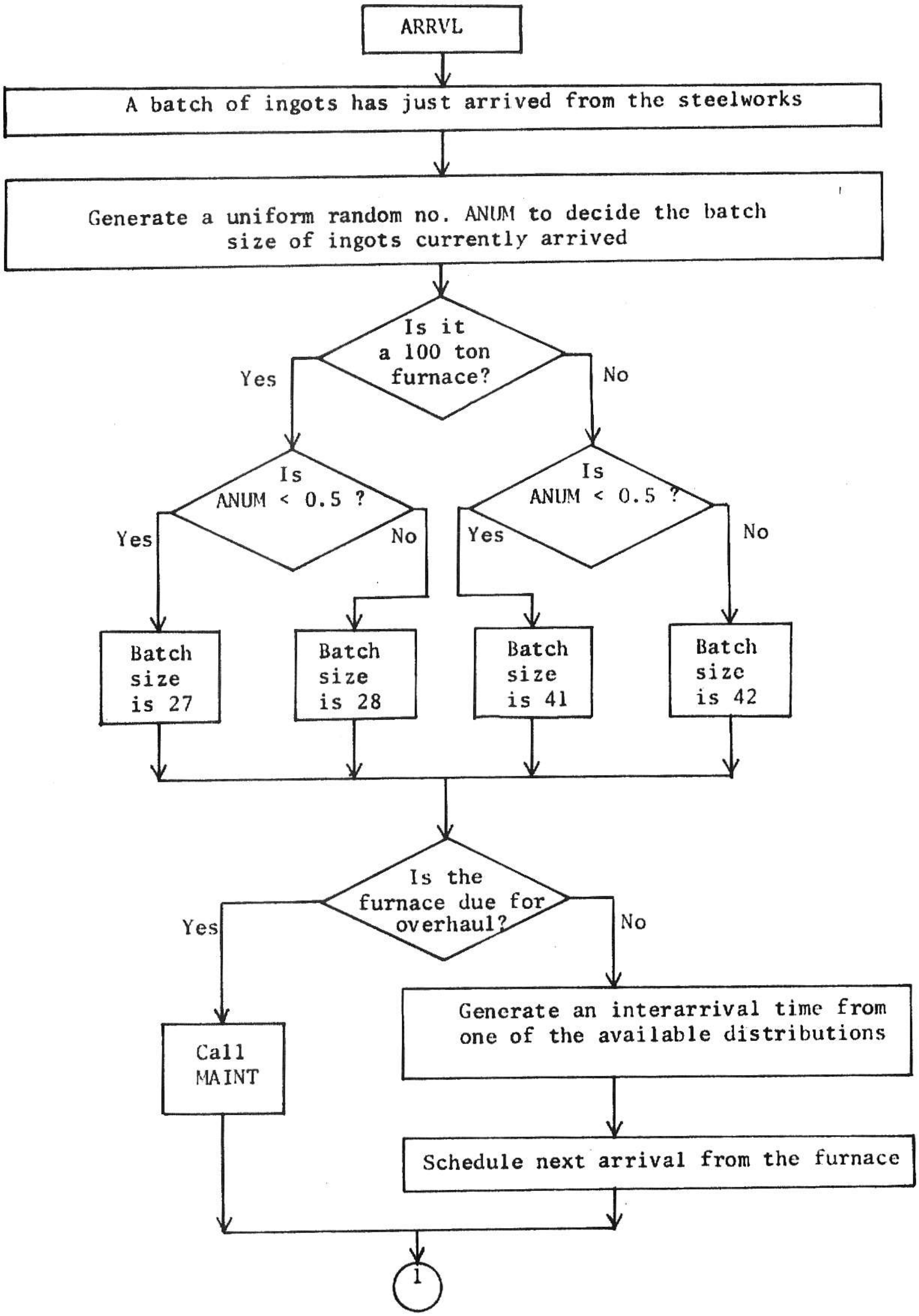

Figure B-3. Subroutine ARRVL

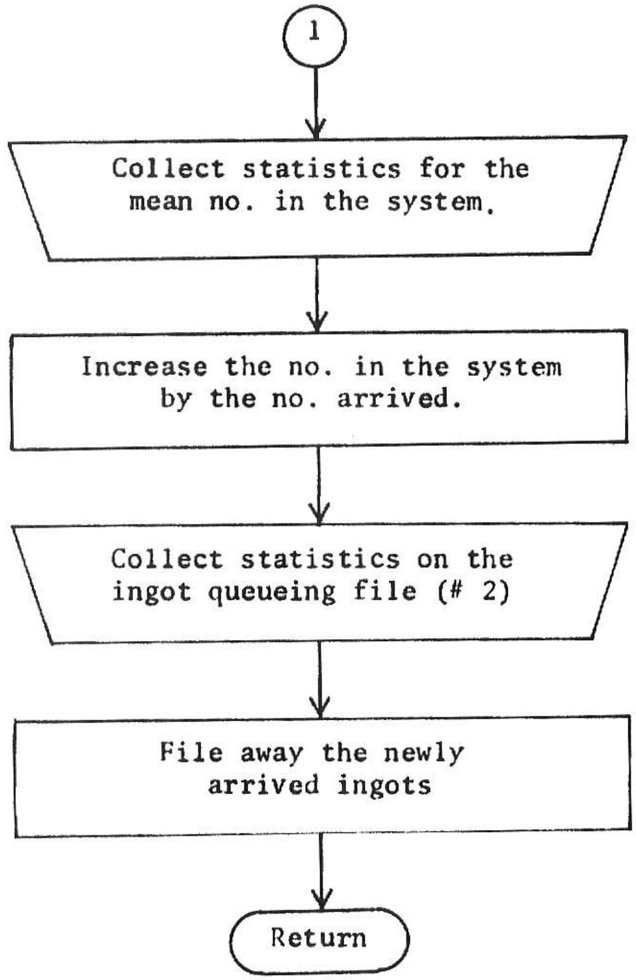

Figure B-3. Subroutine ARRVL (contd.)

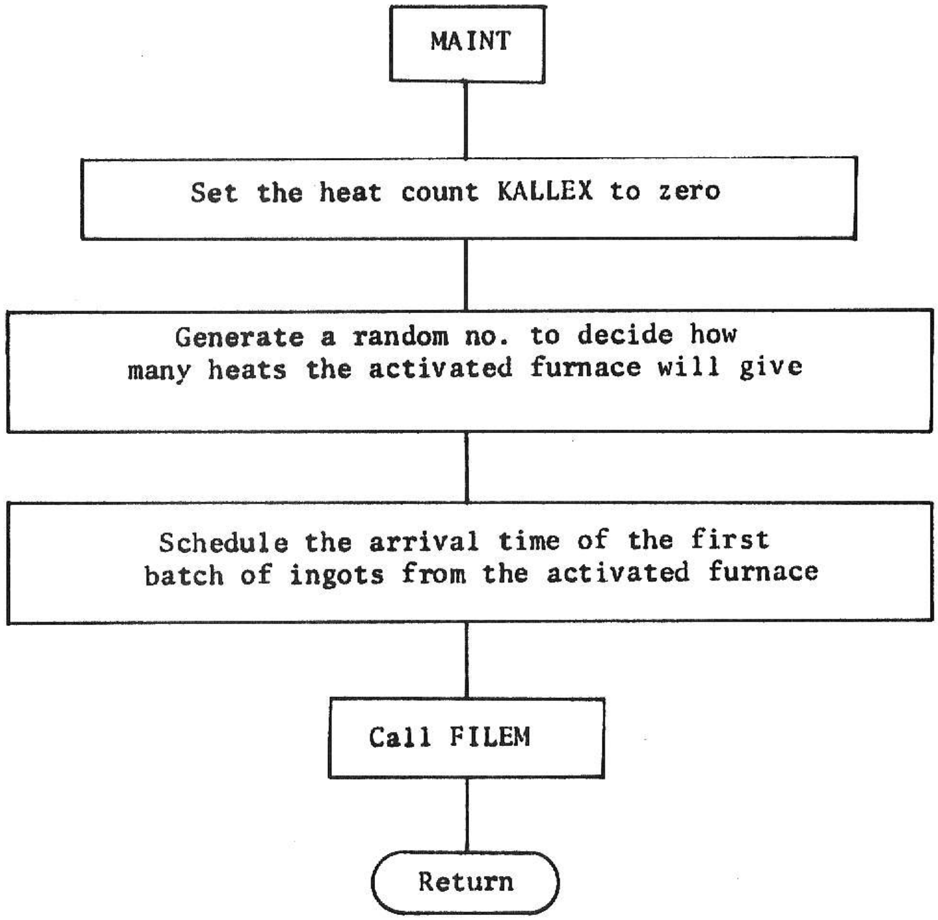

Figure B-4. Subroutine MAINT

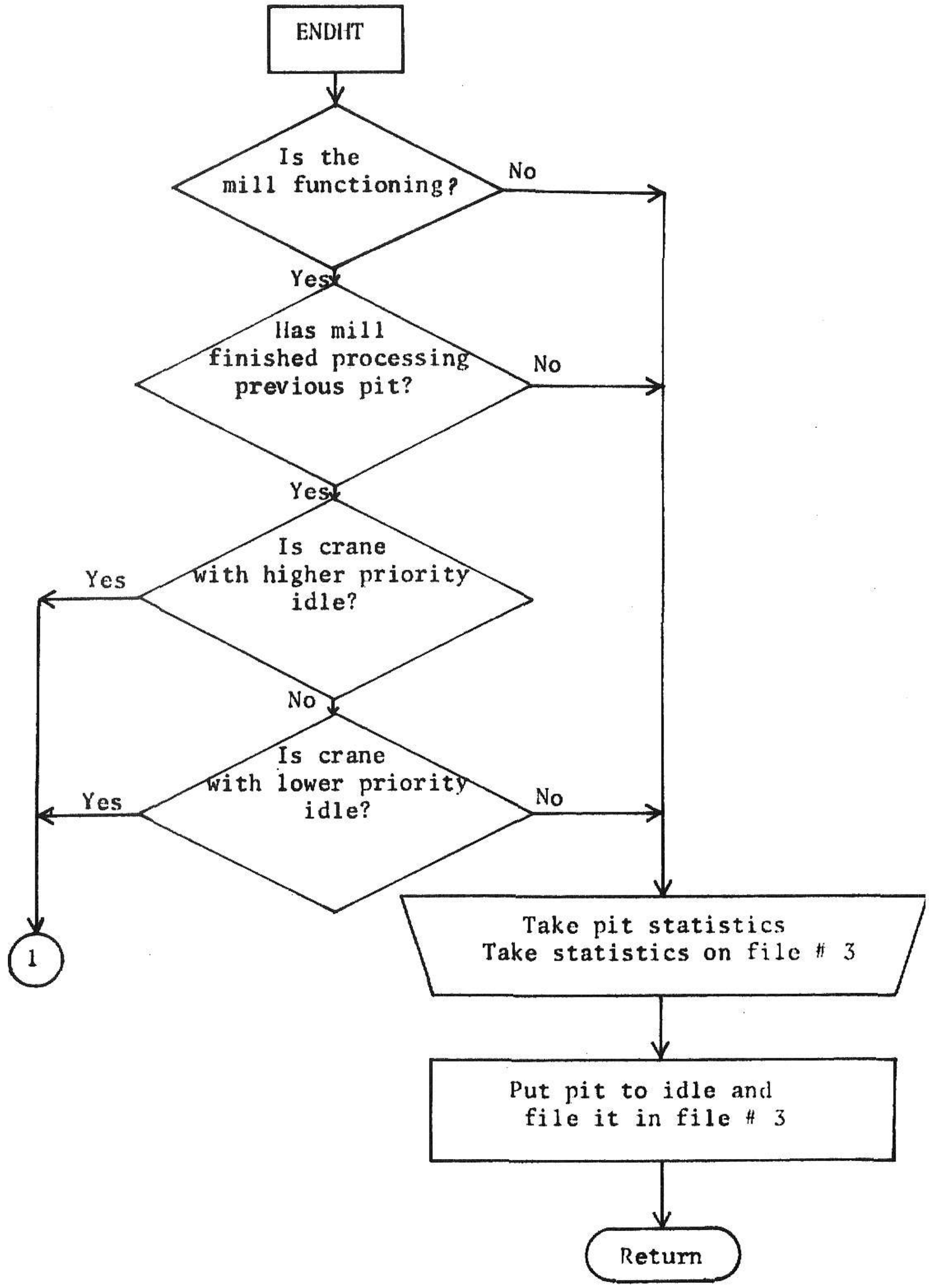

Figure B-5 Subroutine ENDHT

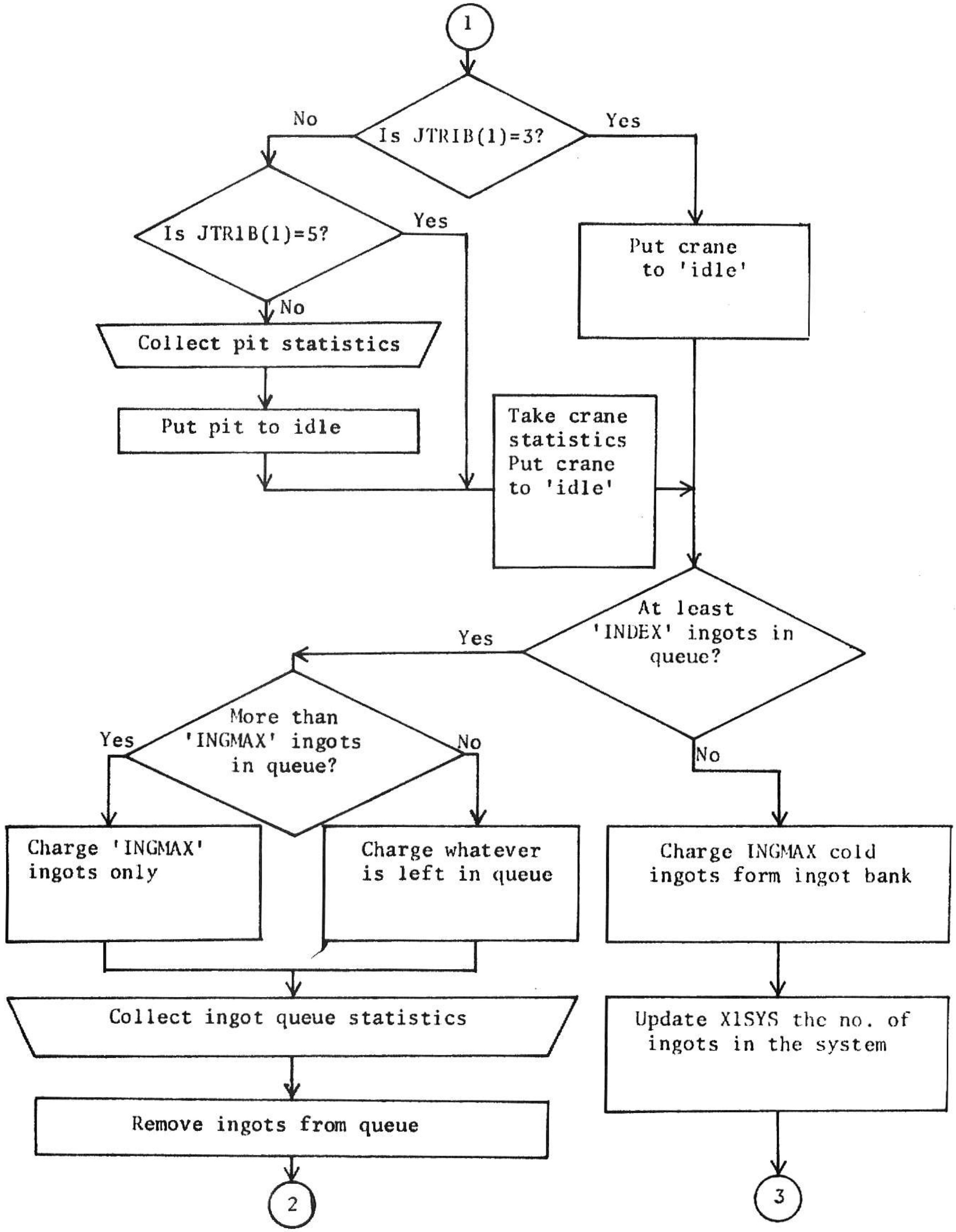

Figure B-5. Subroutine ENDHT (cont'd)

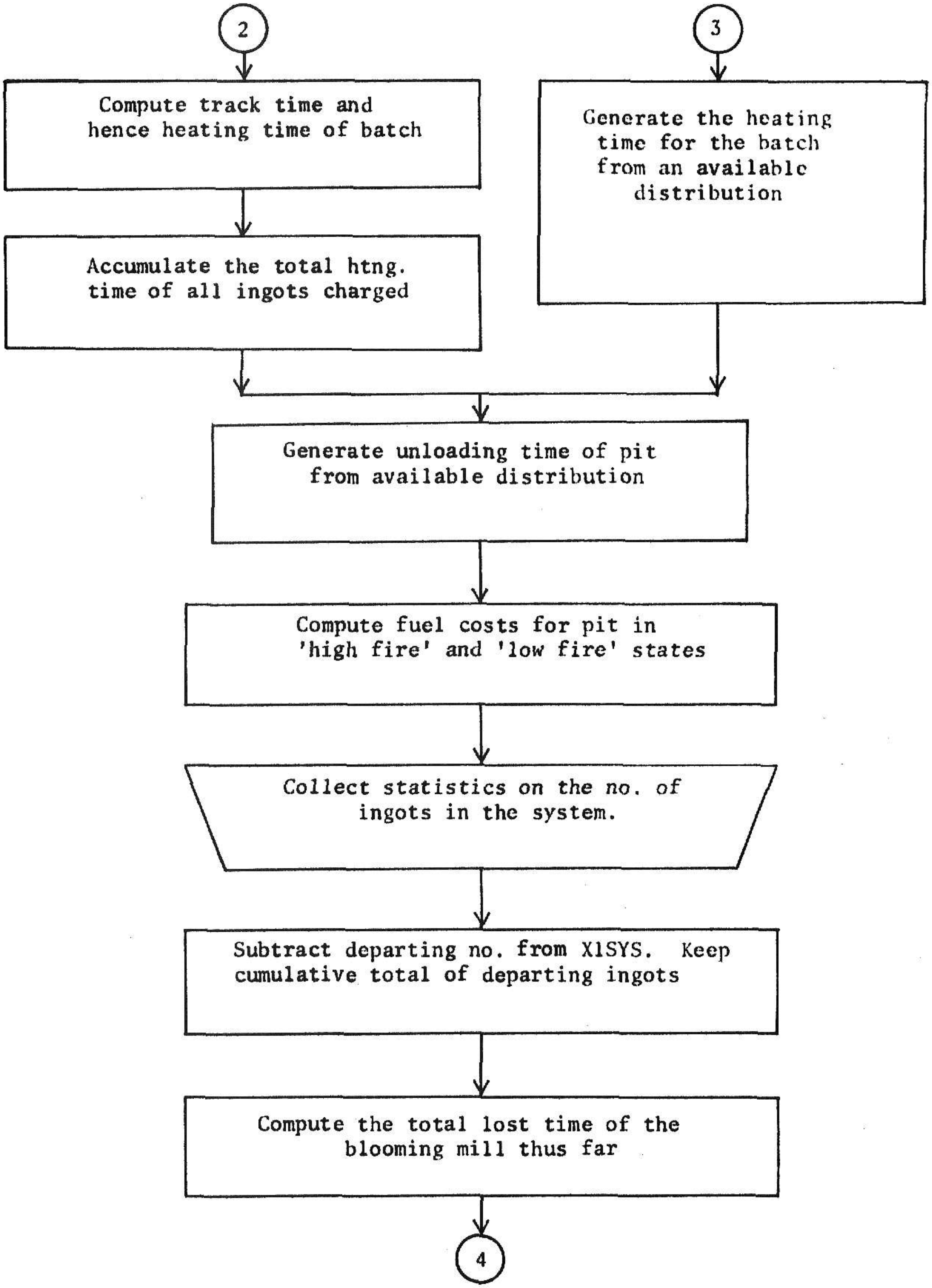

Figure B-5. Subroutine ENDIT (cont'd)

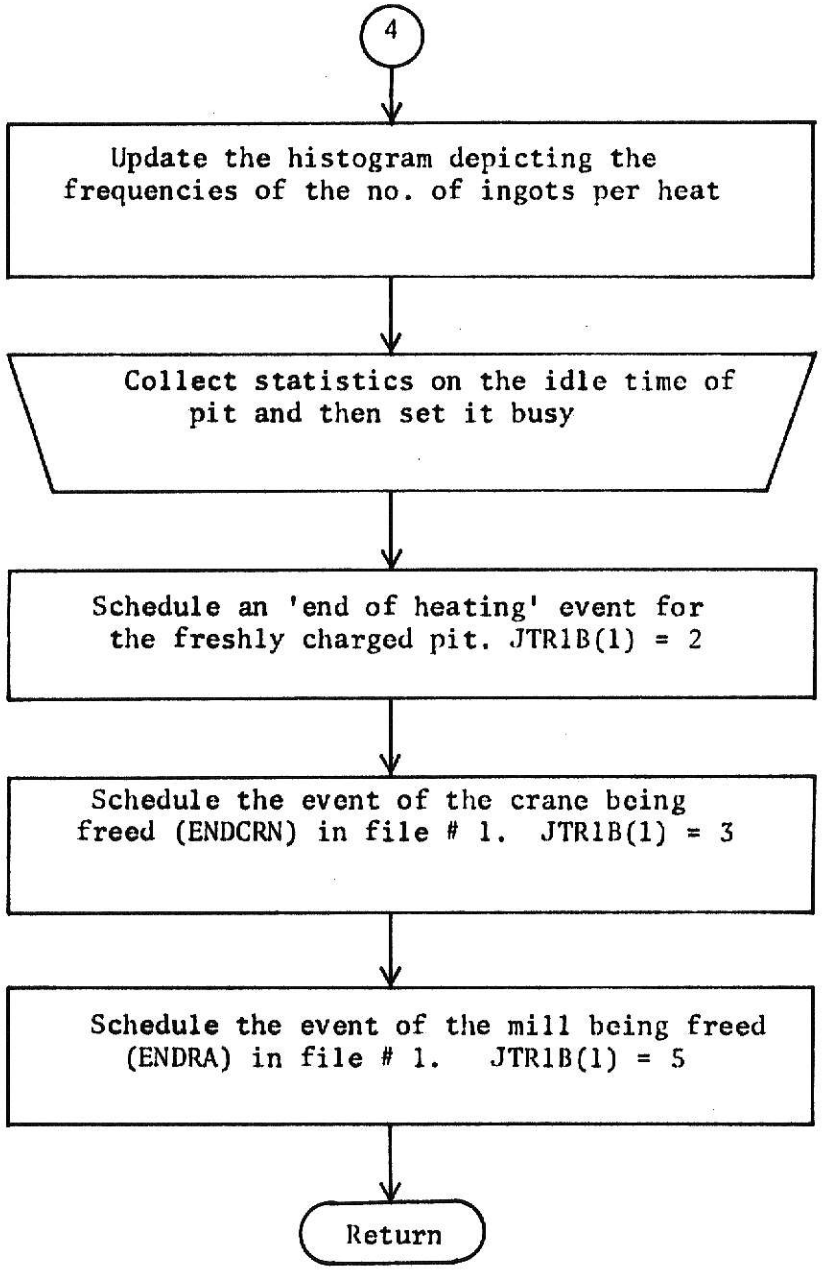

Figure B-5. Subroutine ENDHT (cont'd)

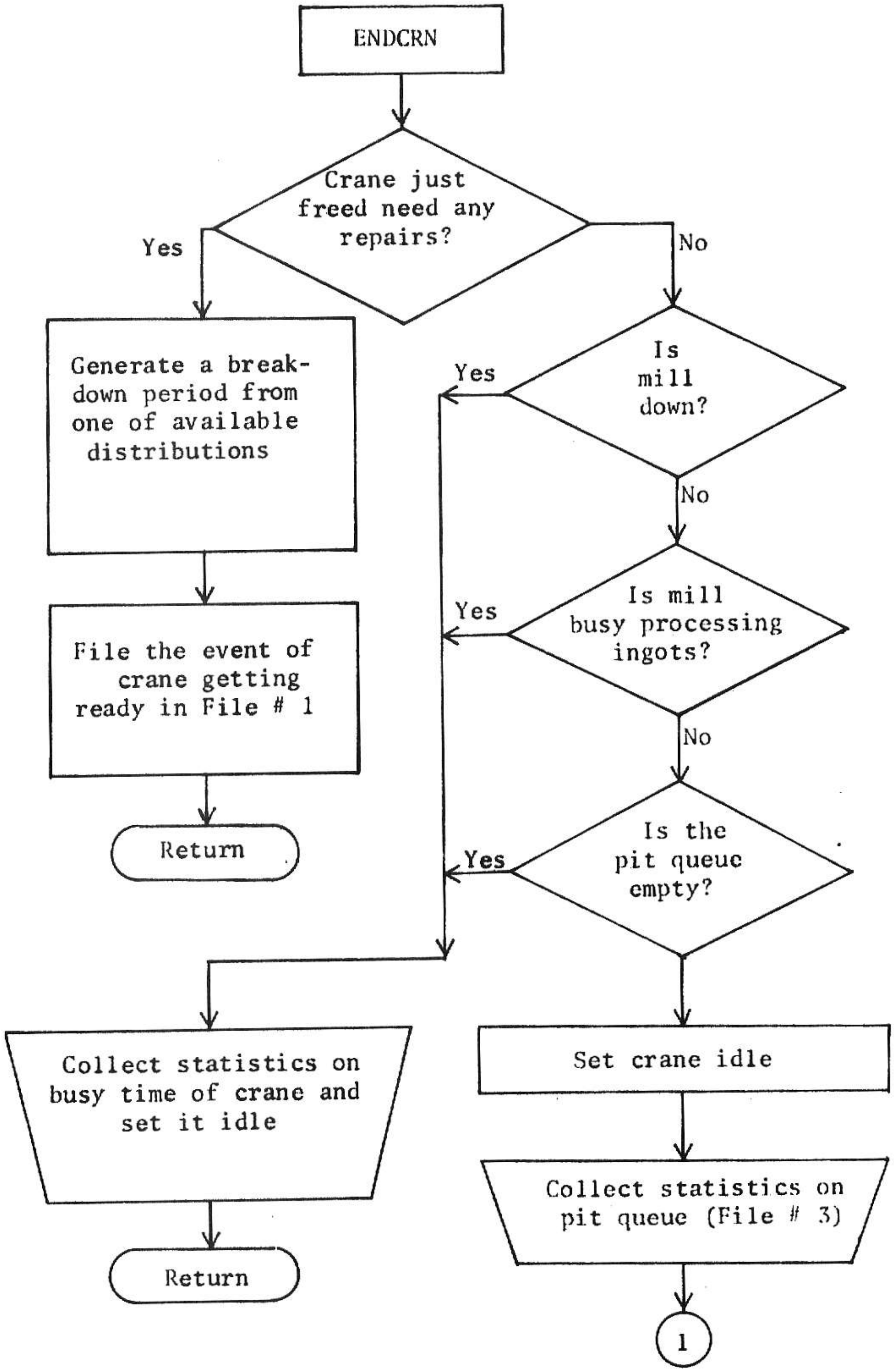

Figure B-6. Subroutine ENDCRN

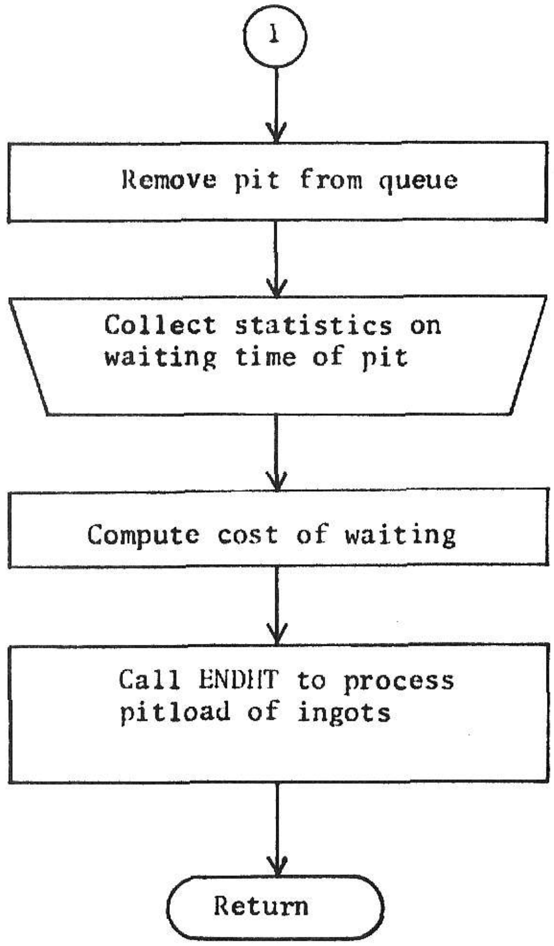

Figure B-6. Subroutine ENDCRN (cont'd)

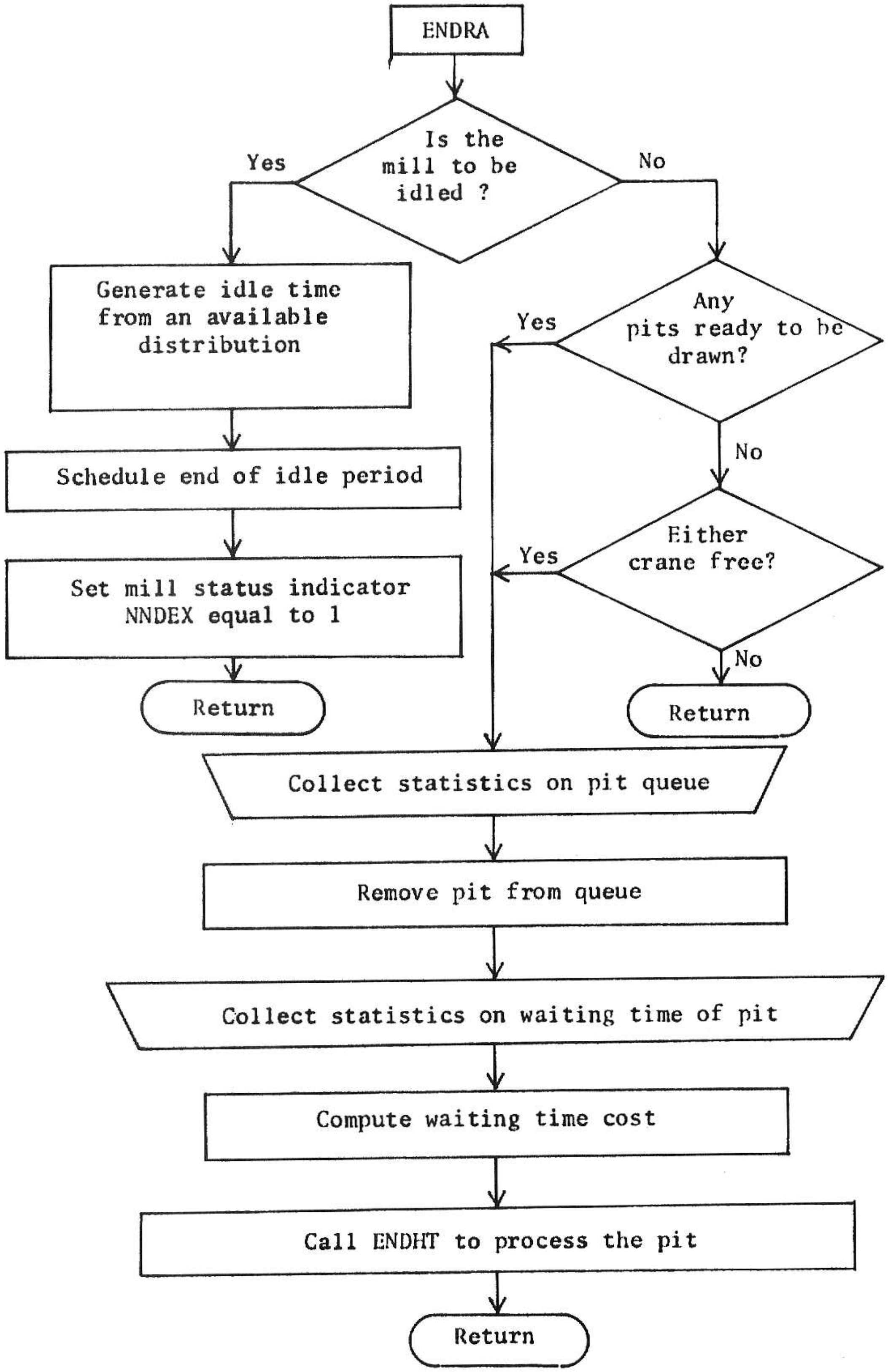

Figure B-7. Subroutine ENDRA

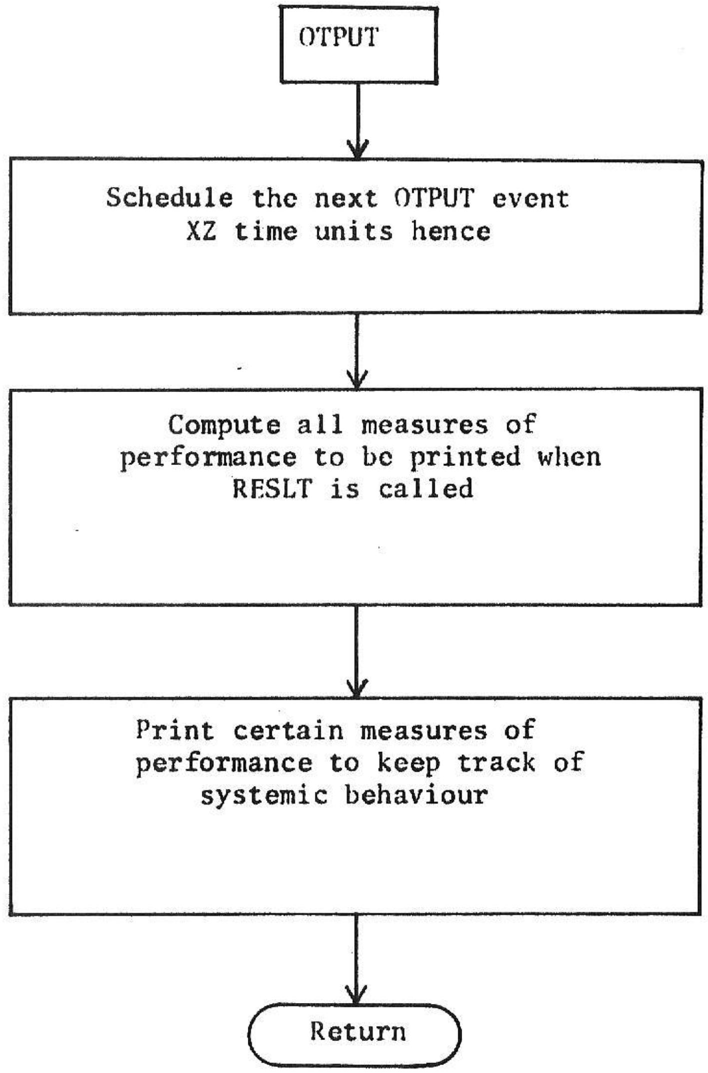

Figure B-8. Subroutine OTPUT

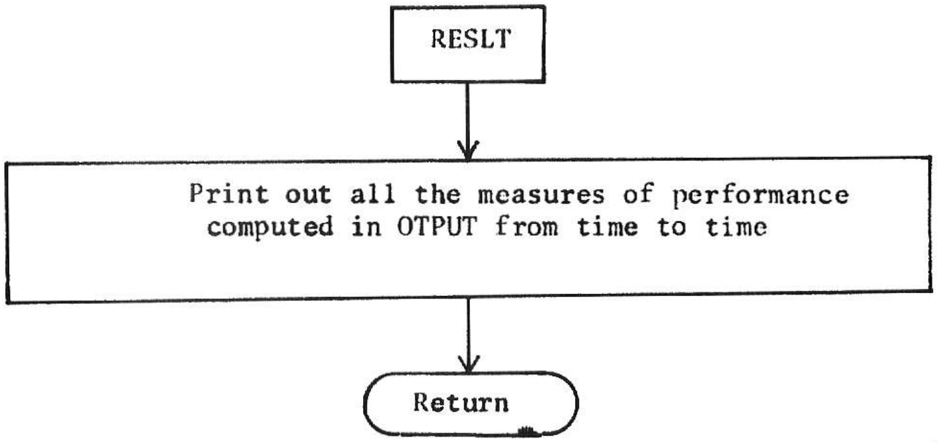

Figure B-9. Subroutine RESLT

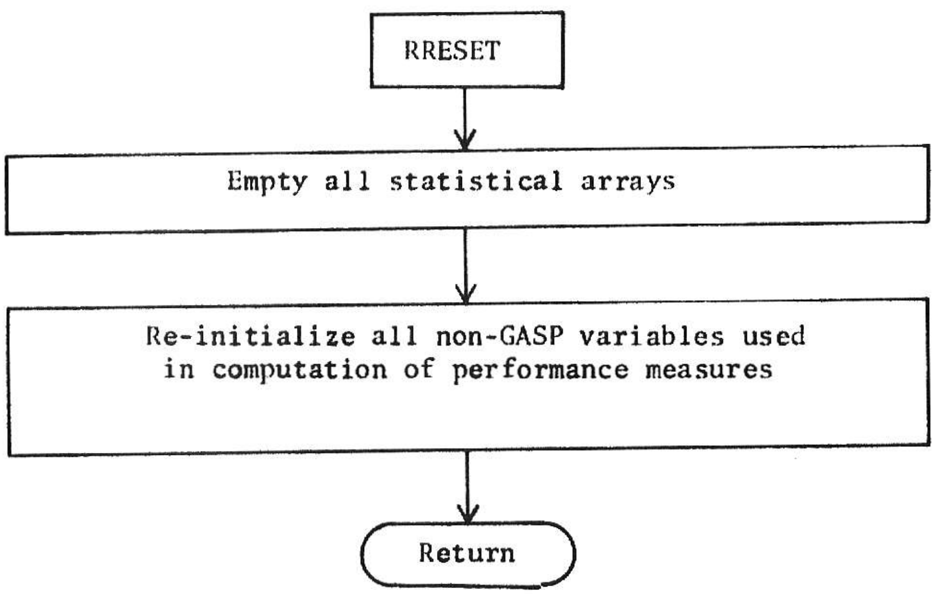

Figure B-10. Subroutine RRESET

APPENDIX C

COMPUTER PROGRAM LISTING

This Appendix contains a listing of the ten user written subroutines used in simulating the pit-mill complex.

```
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(2000),QSET(2000)
C
C***  FOLLOWING VARIABLES HAVE UNIQUELY ASSIGNED VALUES
C***  NCRANE = NO. OF CRANES OPERATING ON PITS
C***  NNDEX = MILL STATUS(BROKEN DOWN OR NOT)INDICATOR
C
      NCRDR=1
      NPRNT=3
      NCRANE=2
      NNDEX=0
C    ******************************************************
C    *                                                    *
C    * FOLLOWING ARE THE FIXED POINT NON-GASP VARIABLES   *
C    *                                                    *
C    *            *** DATA CARD TYPE ONE ***              *
C    * NCRDR = LOGICAL UNIT NO. OF THE INPUT UNIT         *
C    * NPRNT = LOGICAL UNIT NO. OF THE OUTPUT UNIT        *
C    * NCRANE = NO. OF CRANES OPERATING ON SOAKING PITS   *
C    * NPIT = NO. OF SOAKING PITS                         *
C    * NHOT = ACCUMULATED NO. OF INGOTS PRODUCED BY THE   *
C    *        STEELWORKS DURING A RUN                     *
C    * NCOLD = ACCUMULATED NO. OF INGOTS SUPPLIED BY THE  *
C    *        INGOT BANK DURING THE RUN                   *
C    * IV = SUBSCRIPT USED IN ACCUMULATING RUN RESULTS    *
C    * KALLEX(IFUR) = THE HEAT NO. OF THE FURNACE NO. IFUR *
C    * MTRIG(IFUR) = THE NO. OF HEATS AFTER WHICH FURNACE *
C    *              IFUR WILL BE OVERHAULED               *
C    * ITRIG = TIME AFTER WHICH FINAL RESULTS WILL BE     *
C    *        PRINTED                                     *
C    * JFUR = SERIAL NO. OF IDLED FURNACE                 *
```

```
C    * INDEX = MINIMUM NO. OF INGOTS CHARGED TO A FURNACE    *
C    *                                                        *
C    **********************************************************
       READ(NCRDR,40)NPIT,NHOT,NCOLD,IV,
      1(KALLEX(I),I=1,3),(MTRIG(I),I=1,3),ITRIG,JFUR,INDEX
   40 FORMAT(13I5)
C    **********************************************************
C    *                                                        *
C    * FOLLOWING ARE THE FLOATING POINT NON-GASP VARIABLES    *
C    *                                                        *
C    *               *** DATA CARD TYPE TWO ***               *
C    *                                                        *
C    * XZ = TIME INTERVAL BETWEEN COLLECTION OF PERFORMANCE   *
C    *       MEASURES                                         *
C    * ABC = MILL PROCESSING TIME PER INGOT                   *
C    * BBC = MEAN CHARGING TIME PER INGOT                     *
C    * CBC = MAXIMUM HEATING TIME FOR AN INGOT                *
C    * TTHEN = EARLIEST TIME AT WHICH MILL WOULD BE FREE      *
C    * TSEQ = TIME WHEN PIT CURRENTLY BEING DRAWN WOULD       *
C    *         BECOME EMPTY                                   *
C    * TLOST = ACCUMULATED LOST TIME OF MILL DURING RUN       *
C    * TIEM =SIMULATION CLOCK-UPDATED BY 'XZ' WHEN OTPUT      *
C    *         IS CALLED. INITIAL VALUE= ATRIB(1)-XZ          *
C    *                                                        *
C    **********************************************************
       READ(NCRDR,45)XZ,ABC,BBC,CBC,TTHEN,TSEQ,TLOST,TIEM
   45 FORMAT(8F10.4)
C    **********************************************************
C    *                                                        *
C    *               *** DATA CARD TYPE THREE ***             *
C    *                                                        *
C    * SUM1 = ACCUMULATED HEATING TIMES OF INGOTS             *
C    * SUM2 = ACCUMULATED WAITING TIME OF INGOTS IN PITS      *
C    * XMT1 = LOWER LIMIT FOR THE NO. OF HEATS A FURNACE      *
C    *         CAN PRODUCE BEFORE BEING RELINED               *
C    * XMT2 = UPPER LIMIT FOR THE SAME                        *
C    * XISYS = NO. OF INGOTS IN THE SYSTEM                    *
C    * XWT = NET RECOVERY WEIGHT FROM AN INGOT                *
C    * XHRS = AVAILAPLE WORKING HOURS IN A YEAR               *
C    * BDNMIL = FRACTION OF TIME MILL IS DOWN                 *
C    *                                                        *
C    **********************************************************
       READ(NCRDR,45)SUM1,SUM2,XMT1,XMT2,XISYS,XWT,XHRS,BDNMIL
C    **********************************************************
C    *                                                        *
C    *               *** DATA CARD TYPE 4 ***                 *
C    *                                                        *
C    * PCOST = CAPITAL COST OF A PIT PER YEAR                 *
```

```
C    * FCOST = FUEL COST IN DOLLARS PER PIT PER HOUR AT        *
C    *          HIGH FIRE                                      *
C    * HTCOST = ACCUMULATED HEATING COST OF INGOTS AT HIGH     *
C    *           FIRE                                          *
C    * WTCOST = SAME AT LOW FIRE                               *
C    * BLMCST = BLOOMING MILL DOWNTIME COST PER HOUR           *
C    * OPPCST = COST OF LOST OPPOTUNITY PER HOUR               *
C    * XMCST = MAINTENANCE COST PER PIT PER TON                *
C    * BDNCRN = FRACTION OF TIME CRANES ARE DOWN               *
C    *                                                         *
C    ***********************************************************
      READ(NCRDR,45)PCOST,FCOST,HTCOST,WTCOST,BLMCST,OPPCST,
     1XMCST,BDNCRN
C    ***********************************************************
C    *                                                         *
C    *              *** DATA CARD TYPE FIVE ***                *
C    *                                                         *
C    * NUMBER(I) = NO. OF INGOTS IN THE I-TH BATCH TYPE.       *
C    *              A MONOTONOUSLY INCREASING SERIES..         *
C    * INTARL = TYPE OF DISTRIBUTION FOR INTERARRIVAL TIMES *
C    * NCRDST = TYPE OF DISTRIBUTION FOR CRANE BREAKDOWN       *
C    *           DURATION.                                     *
C    * NMLDST = TYPE OF DISTRIBUTION FOR MILL BREAKDOWN        *
C    *           DURATION.                                     *
C    *                                                         *
C    * 1 = UNIFORM     2 = ERLANG     3 = NORMAL               *
C    * ARLMIN,ARLMAX = UNIFORM DIST. LIMITS FOR INTERARRIVAL*
C    * CRMIN,CRMAX =  DITTO FOR CRANE BREAKDOWN DURATIONS      *
C    * XMLMIN,XMLMAX =  DITTO FOR MILL BREAKDOWN DURATIONS     *
C    *                                                         *
C    ***********************************************************
      READ(NCRDR,47)(NUMBER(I),I=1,4),INTARL,NCRDST,NMLDST,
     1ARLMIN,ARLMAX,CRMIN,CRMAX,XMLMIN,XMLMAX
   47 FORMAT(4I4,I2,2I1,6F10.4)
C    ***********************************************************
C    *                                                         *
C    *              *** DATA CARD TYPE SIX ***                 *
C    *                                                         *
C    * QLMT = QUEUE LENGTH LIMIT                               *
C    * POWER = POWER TO WHICH THE QUEUE LIMITING FACTOR IS     *
C    *          RAISED                                         *
C    * COEF = COEFFICIENT OF TRACKTIME IN THE HEATING TIME     *
C    *         FORMULA                                         *
C    * CONST = THE CONSTANT IN THE SAME FORMULA                *
C    * TTLWT = OUTPUT TONNAGE DURING THE RUN                   *
C    * XOTPUT = OUTPUT INGOTS DURING RUN                       *
C    * ICONT = ONLY IF EQUAL TO 1 WILL LIMIT QUEUE LENGTH      *
C    * INGMAX = MAX. INGOTS THAT CAN BE CHARGED TO A PIT       *
```

```
C    * INDRA = TYPE OF DISTRIBUTION FOR INGOT ROLLING TIMES *
C    * INCHG = TYPE OF DISTRIBUTION FOR INGOT CHARGING TIMES*
C    *       1 = ERLANG     2 = NORMAL                        *
C    *                                                         *
C    ***********************************************************
      READ(NCRDR,48)QLMT,POWER,COEF,CONST,TTLWT,XOTPUT,
     1ICONT,INGMAX,INDRA,INCHG
   48 FORMAT(6F10.4,4I5)
C
C***  ECHO CHECK THE INPUT VALUES
C
      WRITE(NPRNT,61)
   61 FORMAT('0','        NPIT      NHOT      NCOLD        IV',
     1'    KALLEX(1) KALLEX(2) KALLEX(3)  MTRIG(1)  MTRIG(2)',
     2'  MTRIG(3)     ITRIG      JFUR     INDEX')
      WRITE(NPRNT,50)NPIT,NHOT,NCOLD,IV,
     1(KALLEX(I),I=1,3),(MTRIG(I),I=1,3),ITRIG,JFUR,INDEX
   50 FORMAT('0',13I10/)
      WRITE(NPRNT,62)
   62 FORMAT('0','        XZ        ABC        BBC        CBC    ',
     1'    TTHEN      TSEQ      TLOST      TIEM')
      WRITE(NPRNT,55)XZ,ABC,BBC,CBC,TTHEN,TSEQ,TLOST,TIEM
      WRITE(NPRNT,63)
   63 FORMAT('0','      SUM1      SUM2      XMT1      XMT2   ',
     1'  XISYS      XWT       XHRS      BDNMIL')
      WRITE(NPRNT,55)SUM1,SUM2,XMT1,XMT2,XISYS,XWT,XHRS,BDNMIL
      WRITE(NPRNT,64)
   64 FORMAT('0','    PCOST      FCOST     HTCOST    WTCOST   ',
     1'  BLMCST   OPPCST     XMCST     BDNCRN')
      WRITE(NPRNT,55)PCOST,FCOST,HTCOST,WTCOST,BLMCST,OPPCST,
     1XMCST,BDNCRN
   55 FORMAT('0',8F10.4/)
      WRITE(NPRNT,65)
   65 FORMAT('0','**(NUMBER(I),I=1,4)** (ARL  CRN  MIL)  AR',
     1'RIVAL LIMITS      CRMIN      CRMAX     XMLMIN     XMLMAX')
      WRITE(NPRNT,56)(NUMBER(I),I=1,4),INTARL,NCRDST,NMLDST,
     1ARLMIN,ARLMAX,CRMIN,CRMAX,XMLMIN,XMLMAX
   56 FORMAT('0',7I5,6F10.4/)
      WRITE(NPRNT,66)
   66 FORMAT('0','    QLMT       POWER      COEF       CONST   ',
     1'  TTLWT   XOTPUT   ICONT NGMAX INDRA INCHG')
      WRITE(NPRNT,57)QLMT,POWER,COEF,CONST,TTLWT,XOTPUT,
     1ICONT,INGMAX,INDRA,INCHG
   57 FORMAT('0',6F10.4,4I5//)
C
C***  SET ALL CRANES AND PITS BUSY
C***  INITIATE PIT STATISTICS VARIABLES(SSOMA)
C
```

```
      DO 81 I=1,NPIT
      BUSP(I)=1.0
      SSOMA(I,1)=0.0
      SSOMA(I,2)=0.0
   81 CONTINUE
      DO 82 I=1,NCRANE
      BUSC(I)=1.0
   82 CONTINUE
      NZ=NPIT
      CALL GASP(NSET,QSET)
      CALL RESLT(NSET,QSET)
      STOP
      END
```

```
      SUBROUTINE EVNTS(IZ,NSET,QSET)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(1),QSET(1)
      GO TO(1,2,3,4,5,6),IZ
    1 CALL ARRVL(NSET,QSET)
      RETURN
    2 CALL ENDHT(NSET,QSET)
      RETURN
    3 CALL ENDCRN(NSET,QSET)
      RETURN
    4 CALL OTPUT(NSET,QSET)
      RETURN
    5 CALL ENDRA(NSET,QSET)
      RETURN
    6 CALL RRESET(NSET,QSET)
      RETURN
      END
```

```
      SUBROUTINE ARRVL(NSET,QSET)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(1),QSET(1)
C*****THIS SUBROUTINE IS CALLED IF MFE(1) OF FILE NO.1 HAS
C*****THE EVENT CODE 1 AT TNOW.
      XQ2=NQ(2)
C*****DESPATCH PROGRAMME CONTROL TO THE RIGHT POINT.
C*****DEPENDING ON THE FURNACE SIZE GENERATE A RANDOM NO.
C******FOR DECIDING THE BATCH SIZE.
      ANUM=DRAND(5)
      IFUR=JTRIB(2)
      IF(IFUR.GT.2) GO TO 34
C*****THE CURRENT ARRIVAL IS A 100 TON HEAT. COMPUTE THE
C*****INTERARRIVAL TIME. DECIDE BATCH SIZE ON THE BASIS OF
C*****ANUM-A UNIFORMLY DISTRIBUTED RANDOM NUMBER.
      IF(ANUM.GE.0.5) GO TO 33
      ITYPE=1
      GO TO 100
   33 ITYPE=2
      GO TO 100
C*****THE CURRENT ARRIVAL IS A 150 TON HEAT. COMPUTE THE INTER
C*****ARRIVAL TIME. DECIDE THE BATCH SIZE ON THE BASIS OF
C*****ANUM - A UNIFORMLY DISTRIBUTED RANDOM NUMBER.
   34 IF(ANUM.GE.0.5) GO TO 35
      ITYPE=3
      GO TO 100
   35 ITYPE=4
C*****UPDATE THE HEAT INDEX AND CHECK IF THE FURNACE IS DUE
C*****FOR A PREVENTIVE MAINTENANCE OVERHAULING.
  100 KALLEX(IFUR)=KALLEX(IFUR)+1
      IF(KALLEX(IFUR).LT.MTRIG(IFUR)) GO TO 36
```

```
C*****CALL MAINTENANCE TO SERVICE THIS PIT AND ACTIVATE A
C*****PREVIOUSLY IDLED PIT.
      CALL MAINT(NSET,QSET)
      GO TO 37
C*****IF THE FURNACE IS FUNCTIONING SATISFACTORILY, SCHEDULE
C*****THE NEXT ARRIVAL TIME OF A HEAT FROM THE SAME FURNACE.
C*****GENERATE AN INTERARRIVAL TIME FOR THE FURNACE THAT
C*****HAS JUST NOW PRODUCED A BATCH OF INGOTS
   36 GO TO(1,2,3),INTARL
    1 TIME=((ARLMAX-ARLMIN)*DRAND(4))+ARLMIN
      GO TO 4
    2 TIME=ERLNG(4,1)
      GO TO 4
    3 TIME=RNORM(4,1)
C*****IF FURNACE OUTPUT IS TO BE CONTROLLED BY A FEEDBACK OF
C*****INFORMATION, THE NEXT STATEMENT IS VALID.
    4 IF(ICONT.EQ.1)TIME=TIME*((XQ2/QLMT)**POWER)
      JTRIB(2)=IFUR
      ATRIB(1)=TNOW+TIME
      CALL FILEM(1,NSET,QSET)
C*****DEFINE THE BATCH QUANTITY OF THE CURRENT ARRIVAL
   37 XARVD=NUMBER(ITYPE)
      NNN=NUMBER(ITYPE)
C*****COLLECT THE TIME INTEGRATED STATISTICS ON THE NO. OF
C*****INGOTS IN THE SYSTEM AND THEN INCREASE THE NO.IN THE
C*****SYSTEM BY THE NO. OF ARRIVALS.
      CALL TMST(XISYS,TNOW,1,NSET,QSET)
      XISYS=XISYS+XARVD
C*****KEEP TRACK OF TOTAL NO. OF HOT INGOTS ENTERING SYSTEM
      NHOT=NHOT+NNN
C*****TAKE TIME INTEGRATED STATISTICS ON FILE NO. 2
      IF(XQ2.LT.0.0)CALL ERROR(53,NSET,QSET)
      CALL TMST(XQ2,TNOW,4,NSET,QSET)
C*****FILE THE ARRIVED INGOTS IN THE HOT INGOT FILE (2).
      ATRIB(2)=TNOW
      DO 21 I=1,NNN
      CALL FILEM(2,NSET,QSET)
   21 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE MAINT(NSET,QSET)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(1),QSET(1)
C*****THE HEAT COUNT OF THE FURNACE TO BE ACTIVATED IS SET
C*****AT ZERO. THIS FURNACE WILL RETURN FOR OVERHAUL AFTER
C*****MTRIG(JFUR) HEATS.
      KALLEX(JFUR)=0.0
      MTRIG(JFUR)=XMT1+(XMT2-XMT1)*DRAND(6)
C*****SCHEDULE THE ARRIVAL OF THE FIRST HEAT FROM THE
C*****RE-ACTIVATED FURNACE
   36 GO TO(1,2,3),INTARL
    1 TIME=((ARLMAX-ARLMIN)*DRAND(4))+ARLMIN
      GO TO 4
    2 TIME=ERLNG(4,1)
      GO TO 4
    3 TIME=RNORM(4,1)
C*****IF FURNACE OUTPUT IS TO BE CONTROLLED BY A FEEDBACK OF
C*****INFORMATION, THE NEXT STATEMENT IS VALID.
    4 IF(ICONT.EQ.1)TIME=TIME*((XQ2/QLMT)**POWER)
      JTRIB(1)=1
      JTRIB(2)=JFUR
      ATRIB(1)=TNOW+TIME
      CALL FILEM(1,NSET,QSET)
C*****JFUR IS NOW THE SERIAL NO. OF THE IDLED FURNACE.
      JFUR=IFUR
      RETURN
      END
```

```
      SUBROUTINE ENDHT(NSET,QSET)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(1),QSET(1)
C*****     THIS SUBROUTINE HAS BEEN CALLED BECAUSE THE FIRST
C*****ENTRY IN FILE NO. 1 IS AN ENDHT. A PITLOAD OF INGOTS
C*****IS READY FOR DRAWING. CHECK TO SEE IF EITHER ONE OF
C*****THE CRANES IS IDLE, WITH CRANE 1 HAVING PRIORITY OVER
C*****PITS 1 THROUGH NZ/2 AND CRANE 2 HAVING PRIORITY OVER
C*****PITS NZ/2 THROUGH NZ.
      IPIT=JTRIB(2)
      L=IPIT
      NINGOT=JTRIB(3)
      IF(NNDEX)707,17,707
   17 IF(TNOW.LT.TSEQ)GO TO 707
      NUM=NZ/2
      IF(IPIT.LE.NUM) GO TO 40
      KK=2
      GO TO 39
   40 KK=1
   39 DO 25 I=1,NCRANE
      IF(KK.EQ.1) GO TO 41
      J=3-I
      GO TO 42
   41 J=I
   42 IF(BUSC(J))25,30,25
   25 CONTINUE
      GO TO 707
C*****IF A PIT IS READY BUT BOTH CRANES ARE NOT, FIND THE
C*****MEAN NO. OF INGOTS HEATED IN THE PIT AS WELL AS ITS
C*****UTILIZATION BY TAKING TIME-INTEGRATED STATISTICS. THEN
C*****SET PIT IDLE.
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```
  707 IRMA=IPIT+5
      XGOT=JTRIB(3)
      CALL TMST(XGOT,TNOW,IRMA,NSET,QSET)
      XGOT=0.0
      TIB=TNOW-SSOMA(L,1)
      SSOMA(L,1)=SSOMA(L,1)+TIB
      SSOMA(L,2)=SSOMA(L,2)+BUSP(IPIT)*TIB
      BUSP(IPIT)=0.0
C*****TAKE TIME INTEGRATED STATISTICS ON THE PIT WAITING
C*****FILE.
      XQ3=NQ(3)
      CALL TMST(XQ3,TNOW,5,NSET,QSET)
C*****FILE THE ATTRIBUTES OF THE PIT. ATRIB(3) IS THE
C*****ARRIVAL TIME IN THE FILE. RETURN TO EVENTS.
      ATRIB(3)=TNOW
      JTRIB(2)=IPIT
      JTRIB(3)=NINGOT
      CALL FILEM(3,NSET,QSET)
      RETURN
C*****IF A PIT IS READY AND A CRANE IS AVAILABLE, COLLECT
C*****STATISTICS ON THE BUSY TIME OF THE PIT AND THE IDLE
C*****TIME OF THE CRANEONLY IF THE EVENT IS AN 'ENDHT'.
C*****THEN SET THE PIT IDLE AND THE CRANE BUSY.
   30 IF(JTRIB(1).EQ.3) GO TO 301
      IF(JTRIB(1).EQ.5) GO TO 717
      XGOT=JTRIB(3)
      IRMA=IPIT+5
      CALL TMST(XGOT,TNOW,IRMA,NSET,QSET)
      XGOT=0.0
      TIB=TNOW-SSOMA(L,1)
      SSOMA(L,1)=SSOMA(L,1)+TIB
      SSOMA(L,2)=SSOMA(L,2)+BUSP(IPIT)*TIB
      BUSP(IPIT)=0.0
  717 LM=J+1
      BUSC1=BUSC(J)
      CALL TMST(BUSC1,TNOW,LM, NSET,QSET)
  301 BUSC(J)=1.0
C*****ARE THERE AT LEAST 'INDEX' INGOTS IN THE QUEUE? IF NOT
C*****FEED COLD INGOTS FROM THE INGOT BANK.
      IF(NQ(2))3,5,5
    3 CALL ERROR(31,NSET,QSET)
      RETURN
    5 IF(NQ(2).GE.INDEX) GO TO 6
C*****TAKE TIME WEIGHTED STATISTICS ON THE TOTAL NO. OF
C*****INGOTS IN THE SYSTEM. INTRODUCE THE 'INGMAX' COLD
C*****INGOTS INTO THE SYSTEM. KEEP TRACK OF COLD INGOTS.
C*****GENERATE HEATING TIME OF CHARGE.
      XNGMAX=INGMAX
```

```
      XISYS=XISYS+XNGMAX
      NINGOT=INGMAX
      NCOLD=NCOLD+INGMAX
      HTIME=CBC-0.5+DRAND(5)
      GO TO 52
C
C*****IF THERE ARE SUFFICIENT NO. OF HOT INGOTS, DECIDE
C*****HOW MANY ARE TO BE FED TO THE PITS.
    6 IF(NQ(2).GT.INGMAX)GO TO 7
      NINGOT=NQ(2)
      GO TO 8
    7 NINGOT=INGMAX
C*****  COLLECT TIME INTEGRATED STATISTICS ON THE QUEUE
C*****LENGTH AND THEN REMOVE THE HOT INGOTS FROM THE
C*****WAITING LINE . TAKE THE WAITING TIME STATISTICS OF THE
C*****QUEUE. COMPUTE THE PIT UNLOADING TIME. THE HEATING
C*****TIME IS BASED ON A ST. LINE RELATIONSHIP.
    8 XQ2=NQ(2)
      CALL TMST(XQ2,TNOW,4,NSET,QSET)
      NP1=JTRIB(1)
      NP2=JTRIB(2)
      NP3=JTRIB(3)
      XP1=ATRIB(1)
      X1=NINGOT
      ST=0.0
      DO 51 K=1,NINGOT
      MFE2=MFE(2)
      CALL RMOVE(MFE2,2,NSET,QSET)
      TWT2=TNOW-ATRIB(2)
      ST=ST+TWT2
      CALL COLCT(TWT2,2,NSET,QSET)
   51 CONTINUE
      JTRIB(1)=NP1
      JTRIB(2)=NP2
      JTRIB(3)=NP3
      ATRIB(1)=XP1
      TRKTIM=ST/X1
      HTIME=COEF*TRKTIM+CONST
      IF(HTIME.GT.CBC)HTIME=CBC
C*****COMPUTE THE TOTAL HEATING TIME 'SUM1' OF ALL THE
C*****HOT INGOTS CHARGED.
      SUM1=SUM1+HTIME*NINGOT
C
C*****COMPUTE THE UNLOADING TIME OF THE PIT CURRENTLY BEING
C*****PROCESSED
   52 UNLOAD=0.0
      IF(INDRA.EQ.2)GO TO 321
      DO 311 I=1,NP3
```

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  311 UNLOAD=UNLOAD+ERLNG(6,4)
      GO TO 322
  321 DO 312 I=1,NP3
  312 UNLOAD=UNLOAD+RNORM(6,4)
C*****COMPUTE CUMULATIVE FUEL COST FOR PITLOAD BOTH WHILE
C*****HEATING AND WHILE UNLOADING
  322 HTCOST=(HTIME*FCOST)+HTCOST
      WTCOST=(UNLOAD*FCOST*0.2)+WTCOST
C*****     DECREASE THE NO. IN THE SYSTEM BY THE NO.
C*****DEPARTING AFTER TAKING TIME INTEGRATED STATISTICS ON
C*****XISYS. FOR THIS PURPOSE THE MIDPOINT OF THE UNLOADING
C*****PERIOD IS THE INSTANTANEOUS POINT OF EXPULSION.
      TIME2=TNOW+(UNLOAD/2.0)
      CALL TMST(XISYS,TIME2,1,NSET,QSET)
      XIT=JTRIB(3)
      XISYS=XISYS-XIT
      IF(XISYS.LT.0.0)CALL ERROR(49,NSET,QSET)
C*****ACCUMULATE OUTPUT OF INGOTS FROM SYSTEM
      XOTPUT=XOTPUT+XIT
C*****COLLECT TOTAL LOST TIME OF BLOOMING MILL
      TBDP=TNOW-TTHEN
      TTHEN=TNOW+UNLOAD
      TLOST=TLOST+TBDP
C*****UPDATE THE HISTOGRAM DEPICTING FREQUENCIES OF INGOT
C*****QUANTITIES CHARGED EACH PIT
      X1=NINGOT
      SCLLM=INDEX+1
      CALL HISTO(X1,SCLLM,1.,IPIT)
C*****COLLECT STATISTICS ON THE IDLE TIME OF THE PIT
C*****AND THEN SET IT BUSY
      XLOAD=0.0
      IF(INCHG.EQ.2)GO TO 323
      DO 313 I=1,NINGOT
  313 XLOAD=XLOAD+ERLNG(7,5)
      GO TO 324
  323 DO 314 I=1,NINGOT
  314 XLOAD=XLOAD+RNORM(7,5)
  324 TIME1=TNOW+UNLOAD+XLOAD
      IRMA=JTRIB(2)+5
      CALL TMST(XGOT,TIME1,IRMA,NSET,QSET)
      TIB=TIME1-SSOMA(L,1)
      SSOMA(L,1)=SSOMA(L,1)+TIB
      SSOMA(L,2)=SSOMA(L,2)+BUSP(IPIT)*TIB
      BUSP(IPIT)=1.0
C*****SCHEDULE AN 'ENDHT' FOR THE FRESHLY CHARGED PIT
C*****BY COLLECTING ALL THE ATTRIBUTES IN FILE NO. 1
      ATRIB(1)=TNOW+UNLOAD+XLOAD+HTIME
      JTRIB(1)=2
```

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      JTRIB(2)=IPIT
      JTRIB(3)=NINGOT
      CALL FILEM(1,NSET,QSET)
C*****FILE THE EVENT OF THE CRANE GETTING FREE IN THE
C*****EVENT FILE.
      ATRIB(1)=TNOW+UNLOAD+XLOAD
      JTRIB(1)=3
      JTRIB(2)=J
      CALL FILEM(1,NSET,QSET)
C*****UPDATE TSEQ TO TNOW+UNLOAD
      TSEQ=TNOW+UNLOAD
C*****SCHEDULE NEXT ENDRA(NSET,QSET)
      ATRIB(1)=TSEQ+0.000001
      JTRIB(1)=5
      CALL FILEM(1,NSET,QSET)
      RETURN
      END
```

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      SUBROUTINE ENDCRN(NSET,QSET)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(1),QSET(1)
C*****    THIS SUBROUTINE IS CALLED WHEN THE FIRST ENTRY IN
C***** THE 'EVNT' FILE IS THE FINISH OF LOADING AND
C*****UNLOADING BY A CRANE. CHECK IF THE CRANE JUST FREED
C*****HAS TO GO IN FOR REPAIRS. IF SO GENERATE THE REPAIR
C*****TIME FROM ONE OF THE AVAILABLE DISTRIBUTIONS
      JQ=JTRIB(2)
      IF(DRAND(JQ).GT.BDNCRN)GO TO 7
      GO TO(11,12,13),NCRDST
   11 TIME=((CRMAX-CRMIN)*DRAND(7))+CRMIN
      GO TO 14
   12 TIME=ERLNG(7,2)
      GO TO 14
   13 TIME=RNORM(7,2)
   14 ATRIB(1)=TNOW+TIME
      CALL FILEM(1,NSET,QSET)
      RETURN
    7 ICRANE=JTRIB(2)
      BUSC1=BUSC(ICRANE)
C*****IF MILL IS NOT IN A BREAKDOWN STATE,CHECK IF IT HAS
C*****FINISHED PROCESSING THE PREVIOUS PITLOAD OF INGOTS
      IF(NNDEX)4,9,4
    9 IF(TNOW.LT.TSEQ) GO TO 4
C*****WHAT IS THE STATUS OF THE PIT-WAITING FILE?
      IF(NQ(3))3,4,5
    3 CALL ERROR(32,NSET,QSET)
      RETURN
C*****IF THE MILL IS BROKEN DOWN OR BUSY OR IF THERE ARE NO
C*****PITS READY FOR UNLOADING,COLLECT STATISTICS ON THE
```

```
C*****BUSY TIME OF THE CRANE AND THEN SET IT IDLE
    4 LP=ICRANE+1
      CALL TMST(BUSC1,TNOW,LP,NSET,QSET)
      BUSC(ICRANE)=0.0
      RETURN
C*****IF THERE IS AT LEAST ONE PIT WAITING, SET THE CRANE
C*****IDLE IN ORDER TO FACILITATE THE USE OF 'ENDHT'. TAKE
C*****TIME INTEGRATED STATISTICS ON QUEUE LENGTH AND
C*****REMOVE THE FIRST PIT FROM THE FILE.
    5 BUSC(ICRANE)=0.0
      MFE3=MFE(3)
      XQ3=NQ(3)
      CALL TMST(XQ3,TNOW,5,NSET,QSET)
      CALL RMOVE(MFE3,3,NSET,QSET)
C*****   COLLECT STATISTICS ON THE WAITING TIME OF THE
C*****PIT REMOVED. KEEP TRACK OF THE NO. OF INGOTS IN THE
C*****OUTCOMING PIT. CALL 'ENDHT' TO SERVICE THE PIT.
C*****RETURN TO 'EVNTS' AND THENCE TO GASP.
      TWT3=TNOW-ATRIB(3)
      WTCOST=(TWT3*FCOST*0.2)+WTCOST
      AGOT=JTRIB(3)
      CALL COLCT(AGOT,1,NSET,QSET)
      CALL COLCT(TWT3,3,NSET,QSET)
      SUM2=SUM2+TWT3*AGOT
      JTRIB(1)=3
      ATRIB(3)=0.0
      CALL ENDHT(NSET,QSET)
      RETURN
      END
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```
      SUBROUTINE ENDRA(NSET,QSET)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(1),QSET(1)
C*****THE MILL HAS JUST FINISHED PROCESSING A PITLOAD OF INGOTS
C*****OR BEEN REPAIRED. IF THE MILL HAS TO BE IDLED(BREAKDOWN
C*****OR SIZE CHANGE), GENERATE THE IDLE TIME FROM AN AVAILABLE
C*****DISTRIBUTION. SCHEDULE NEXT ENDRA.
      IF(DRAND(3).GT.BDNMIL)GO TO 2
      GO TO (11,12,13),NMLDST
   11 TIME=((XMLMAX-XMLMIN)*DRAND(8))+XMLMIN
      GO TO 14
   12 TIME=ERLNG(8,3)
      GO TO 14
   13 TIME=RNORM(8,3)
   14 ATRIB(1)=TNOW+TIME
      CALL FILEM(1,NSET,QSET)
C*****SET MILL STATUS INDEX TO INDICATE 'BREAKDOWN'
      NNDEX=1
      RETURN
C*****SET INDICATOR TO SHOW MILL IS FUNCTIONING
    2 NNDEX=0
      IF(NQ(3))3,4,5
    3 CALL ERROR(41,NSET,QSET)
      RETURN
    4 RETURN
C*****CHECK IF A CRANE IS FREE. IF YES, CHECK FOR READY
C*****PITS. IF NOT, RETURN TO GASP
    5 DO 6 I=1,NCRANE
      IF(BUSC(I).EQ.0.0)GO TO 7
    6 CONTINUE
      RETURN
```

```
C*****IF A PIT IS WAITING REMOVE IT FROM FILE AFTER TAKING
C*****TIME-INTEGRATED STATISTICS ON QUEUE LENGTH AND THEN
C*****CALL ENDHT
    7 MFE3=MFE(3)
      XQ3=NQ(3)
      CALL TMST(XQ3,TNOW,5,NSET,QSET)
      CALL RMOVE(MFE3,3,NSET,QSET)
C*****   COLLECT STATISTICS ON THE WAITING TIME OF THE
C*****PIT REMOVED. KEEP TRACK OF THE NO. OF INGOTS IN THE
C*****OUTCOMING PIT. CALL 'ENDHT' TO SERVICE THE PIT.
C*****RETURN TO 'EVNTS' AND THENCE TO GASP.
      TWT3=TNOW-ATRIB(3)
      WTCOST=(TWT3*FCOST*0.2)+WTCOST
      AGOT=JTRIB(3)
      CALL COLCT(AGOT,1,NSET,QSET)
      CALL COLCT(TWT3,3,NSET,QSET)
      SUM2=SUM2+TWT3*AGOT
      JTRIB(1)=5
      ATRIB(3)=0.0
      CALL ENDHT(NSET,QSET)
      RETURN
      END
```

```
      SUBROUTINE OTPUT(NSET,QSET)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(1),QSET(1)
C*****     THIS SUBROUTINE IS CALLED EVERY 'XZ' TIME UNITS
C*****TO PRINT OUT THE REQUIRED STATISTICS. IN ADDITION ,
C*****GASP CALLS IT ONCE AT THE END OF THE SIMULATION RUN.
C*****PRINT THE HEADING.
      WRITE(NPRNT,555)TNOW
  555 FORMAT('0',40X,'INTERMEDIATE RESULTS AT TIME=',
     1F7.3,/)
C*****FILE THE TIME OF THE NEXT PRINTOUT IN THE EVENT FILE.
      IV=IV+1
      ATIME(IV)=TNOW
      ATRIB(1)=TNOW+XZ
      JTRIB(1)=4
      CALL FILEM(1,NSET,QSET)
C*****COMPUTE CRANE UTILIZATION AS A FRACTION.
      DO 62 IQ=1,NCRANE
      JQ=IQ+1
      BK(IV,IQ)=SSUMA(JQ,2)/SSUMA(JQ,1)
   62 CONTINUE
C*****PRINT THE AVERAGE WAITING TIME OF INGOTS IN FILE NO.2
C*****BEFORE BEING CHARGED TO THE PITS.
      EK(IV)=SUMA(2,1)/SUMA(2,3)
C*****AVG. WAITING TIME OF INGOTS BEFORE BEING DRAWN
C*****FROM PITS.
      FK(IV)=SUM2/SUMA(1,1)
C*****AVG. NO. OF INGOTS IN WAITING LINE BEFORE THE PITS.
      GK(IV)=SSUMA(4,2)/SSUMA(4,1)
      WRITE(NPRNT,449)GK(IV),SSUMA(4,4),SSUMA(4,5)
  449 FORMAT('0',' AVG. NO. OF INGOTS IN FILE NO. 2=',
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     1F8.3,' MIN. AND MAX.=',2F6.1)
C*****AVG. NO. OF PITS IN FILE 3 AWAITING SERVICE.
      HK(IV)=SSUMA(5,2)/SSUMA(5,1)
      WRITE(NPRNT,450)HK(IV),SSUMA(5,4),SSUMA(5,5)
  450 FORMAT('0','AVG. NO. OF PITS IN FILE NO. 3=',
     1F8.3,' MIN. AND MAX.=',2F5.1)
C*****AVG. HEATING TIME OF HOT INGOTS ONLY.
      OK(IV)=SUM1/NHOT
C*****AVERAGE NO. OF INGOTS IN THE SYSTEM.
      PK(IV)=SSUMA(1,2)/SSUMA(1,1)
C*****ACCUMULATED NO. OF HOT AND COLD INGOTS PASSING
C*****THROUGH THE SYSTEM.
      XTTL=NHOT+NCOLD
      WRITE(NPRNT,453)NHOT,NCOLD,XTTL,XOTPUT
  453 FORMAT('0',' TOTAL NO. OF HOT INGOTS=',I5,4X,
     1'COLD INGOT INPUT=',I5,' INPUT TOTAL=',F8.1,
     2'  INGOT OUTPUT FROM SYSTEM=',F8.1)
C*****TOTAL INPUT TO THE SYSTEM THUS FAR IN TONS.
      TTLWT1=XTTL*XWT
C*****CALCULATE RATIOS NCOLD/NHOT AND TONS/HOUR INPUT
      XHOT=NHOT
      XCOLD=NCOLD
      XRATIO(IV)=XCOLD/XHOT
      TIEM=TIEM+XZ
      XINRET(IV)=TTLWT1/TIEM
C*****GET THE ACCUMULATED PRODUCTION RATE
      TTLWT2=TTLWT
      TTLWT=XOTPUT*XWT
      PRATE(IV)=TTLWT/TIEM
C*****GET NON-ACCUMULATED PRODUCTION RATE
      WTBTWN=TTLWT-TTLWT2
      PBTWN(IV)=WTBTWN/XZ
C*****ACCUMULATED BLOOMING MILL IDLE TIME
      WRITE(NPRNT,455)TLOST
  455 FORMAT('0',' TOTAL BLOOMING MILL IDLE TIME=',F8.3,///)
C
C*****CALCULATIONS LEADING TO TOTAL COST PER FINISHED TON
C*****FOR THE CURRENT SETUP
C
C*****FUEL COST PER TON (FUEL) IS COMPUTED
      FUEL(IV)=(HTCOST+WTCOST)/TTLWT
C*****CAPITAL COST PER TON (CCOST) IS COMPUTED
      XPIT=NPIT
      CCOST(IV)=(PCOST*XPIT*TIEM)/(XHRS*TTLWT)
C*****MAINTENANCE COST PER TON (XMCOST) IS COMPUTED
      XMCOST(IV)=(XPIT/12.0)*((112.5*TIEM)/TTLWT)*XMCST
C*****COST DUE TO DOWNTIME OF MILL (DTCOST) PER TON OUTPUT
C*****IS CALCULATED.
```

```
      DTCOST(IV)=(TLOST*(BLMCST+(OPPCST*PRATE(IV))))/TTLWT
C*****TOTAL COST PER FINISHED TON IS THE SUM OF THE COSTS
      TTLCST(IV)=FUFL(IV)+CCOST(IV)+XMCOST(IV)+DTCOST(IV)
      RETURN
      END
```

```
      SUBROUTINE RESLT(NSET,QSET)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(1),QSET(1)
      WRITE(NPRNT,11)
   11 FORMAT('1',55X,'SIMULATION  RESULTS')
      WRITE(NPRNT,12)
   12 FORMAT(' ',55X,'*******************',/)
      WRITE(NPRNT,13)NPIT,INDEX
   13 FORMAT(' ',34X,'NO. OF SOAKING PITS=',I3,3X,
     1'MINM. CHARGE=',I3,3X,'QUEUE DISCIPLINE=')
      WRITE(NPRNT,19)
   19 FORMAT('0',130(1H*))
      WRITE(NPRNT,14)
   14 FORMAT('0','TIME      CRANE     AVG.WTNG.AVG.WTNG. ',
     1'AVG.NO.  AVG.NO. AVG.HTNG. AVG.NO.   COLD   FINISH',
     2'ED  FUEL  CAPITAL  MAINT. DOWNTIME  TOTAL')
      WRITE(NPRNT,15)
   15 FORMAT(' ','LAPSE UTILIZATION  TIME OF  TIME OF OF I',
     1'NGOTS OF PITS  TIME OF OF INGOTS BY HOT    TONS    ',
     2'COST    COST    COST    COST  REHEATING')
      WRITE(NPRNT,16)
   16 FORMAT(' ',' IN                     INGOTS   S.PITS  IN ',
     1'QUEUE  IN QUEUE   HOT   IN SYSTEM  RATIO  PER HOUR ',
     2'PER TON PER TON PER TON PER TON  COST')
      WRITE(NPRNT,17)
   17 FORMAT(' ','HOURS    1      2',40X,'INGOTS',61X,'PER TON')
      WRITE(NPRNT,19)
      JA=IV-1
      DO 5 I=1,JA
      WRITE(NPRNT,18)ATIME(I ),BK(I ,1),BK(I ,2),EK(I ),
     1FK(I ),GK(I ),HK(I ),OK(I ),PK(I ),XRATIO(I ),
```

```
     2PRATE(I ),FUEL(I ),CCOST(I ),XMCOST(I ),DTCOST(I ),
     3TTLCST(I )
   18 FORMAT(' ',F5.1,2F6.3,F8.3,F9.3,F9.2,2F9.3,F10.2,
     1F8.3,F8.2,F9.3,F8.2,3F8.3)
    5 CONTINUE
      WRITE(NPRNT,19)
      WRITE(NPRNT,92)
   92 FORMAT('1')
      WRITE(NPRNT,20)
   20 FORMAT('0','TIME   N.C.OTPUT   XINRET(IV)')
      DO 6 I=1,JA
      WRITE(NPRNT,21)ATIME(I),PBTWN(I),XINRET(I)
   21 FORMAT(' ',F6.1,3X,F6.1,5X,F6.1)
    6 CONTINUE
C*****COMPUTE THE MEAN NO. OF INGOTS HEATED IN EACH PIT.
C*****ALSO CALCULATE THE FRACTIONAL UTILIZATION OF EACH PIT
      WRITE(NPRNT,444)
  444 FORMAT('1')
      DO 61 IZ=1,NZ
      JZ=IZ+5
      DK=SSUMA(JZ,2)/SSUMA(JZ,1)
      DL=SSOMA(IZ,2)/SSOMA(IZ,1)
      WRITE(NPRNT,445)IZ,DK,DL,SSUMA(JZ,4),SSUMA(JZ,5)
  445 FORMAT(' ',30X,I2,' MEAN NO. HTD.=',F6.2,' UTILIZATION=',
     1F5.3,'  MIN. AND MAX. ARE',2F5.1)
   61 CONTINUE
      WRITE(NPRNT,145)
  145 FORMAT(///)
      DO 91 N=1,NPIT
      NRY=NCELS(N)+2
      WRITE(NPRNT,556)N,(JCELS(N,J),J=1,NRY)
  556 FORMAT(' ',33X,'FREQUENCIES FOR PIT NO.',I2,6X,16I4)
   91 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE RRESET(NSET,QSET)
      COMMON ID,IM,INIT,JEVNT,JMNIT,MFA,MSTOP,MX,MXC,NCLCT,
     1NHIST,NOQ,NORPT,NOT,NPRMS,NRUN,NRUNS,NSTAT,OUT,TNOW,
     2TBEG,TFIN,MXX,NPRNT,NCRDR,NEP,VNQ(14),IMM,MAXQS,
     3MAXNS,ATRIB(10),ENQ(14),INN(14),JCELS(20,30),
     4KRANK(14),MAXNQ(14),MFE(14),MLC(14),NCELS(20),NQ(14),
     5PARAM(20,4),QTIME(14),SSUMA(25,5),SUMA(25,5),NAME(6),
     6NPROJ,MON,NDAY,NYR,JCLR,JTRIB(12),IX(8),MLE(14)
      COMMON IPIT,NPIT,NCRANE,ICRANE,BUSP(40),BUSC(2),
     1XISYS,NINGOT,ITYPE,NUMBER(10),XARVD,NCOLD,INDEX,SUM2,
     2SUM1,SSOMA(25,2),XQ3,XQ2,NHOT,NNDEX,ITRIG,NZ,LZ,INDRA,
     3KALLEX(4),MTRIG(4),IFUR,JFUR,XMT1,XMT2,TSEQ,ABC,BBC,
     4CBC,TTHEN,TLOST,PCOST,XHRS,XWT,FCOST,WTCOST,HTCOST,
     5OPPCST,IV,BK(60,2),EK(60),FK(60),GK(60),HK(60),OK(60),
     6PK(60),FUEL(60),CCOST(60),XMCOST(60),DTCOST(60),XZ,
     7TTLCST(60),XRATIO(60),PRATE(60),BLMCST,ATIME(60),XMCST,
     8BDNMIL,BDNCRN,TTLWT,XOTPUT,TIEM,PBTWN(60),XINRET(60)
      COMMON INTARL,NCRDST,NMLDST,ARLMIN,ARLMAX,CRMIN,CRMAX,
     1XMLMIN,XMLMAX,QLMT,POWER,COEF,CONST,ICONT,INGMAX,INCHG
      DIMENSION NSET(1),QSET(1)
C*****THIS SUBROUTINE IS CALLED WHEN THE SYSTEM HAS STABILIZED
      DO 10 I=1,NCLCT
      DO 9 J=1,3
    9 SUMA(I,J)=0.0
      SUMA(I,4)=1.0E20
   10 SUMA(I,5)=-1.0E20
      DO 20 I=1,NSTAT
      DO 19 J=1,3
   19 SSUMA(I,J)=0.0
      SSUMA(I,4)=1.0E20
   20 SSUMA(I,5)=-1.0E20
      DO 30 I=1,NHIST
      DO 30 J=1,MXC
   30 JCELS(I,J)=0
      NHOT=0
      NCOLD=0
      TLOST=0.0
      SUM1=0.0
      SUM2=0.0
      TTLWT=0.0
      XOTPUT=0.0
      TIEM=0.0
      DO 40 I=1,NPIT
      SSOMA(I,1)=0.0
   40 SSOMA(I,2)=0.0
      RETURN
      END
```

APPENDIX D

HISTOGRAMS OF GENERATED FREQUENCIES

This Appendix contains histograms of the interarrival, crane and mill breakdown times for the exponential as well as the erlang 4 truncated distributions. The effect of truncation of these distributions on the final results is briefly explained.

Note. Figures D-1 through D-6 depict the relative frequencies of the actual interarrival, crane and mill breakdown times generated by the computer program. Owing to truncation, the actual mean of the exponential distribution for interarrival times of ingot batches would tend to be slightly greater than the desired mean. The truncation values have been set in accordance with the meaningful time limits for the physical processes.

The warping of the Erlang 4 distribution has been more severe. The accumulation of the probability area to the extent of 90% at the upper truncation limit for the three processes indicates that the means of the interarrival, crane and mill breakdown times are well above the desired values. The observed means would have been even greater had there been no truncation on the higher side. Hence the shifting of the mean is entirely due to erroneous generation of random numbers in the case of Erlang 4 distribution. Truncation has only reduced the severity of the distortion. This explains the large consumption of cold ingots as well as the almost doubled mill downtime cost for Sets C and D. As a result of the truncation, whenever the terms 'exponential' or 'erlang 4' are encountered they are to be understood as 'truncated exponential' and 'truncated erlang 4' respectively.

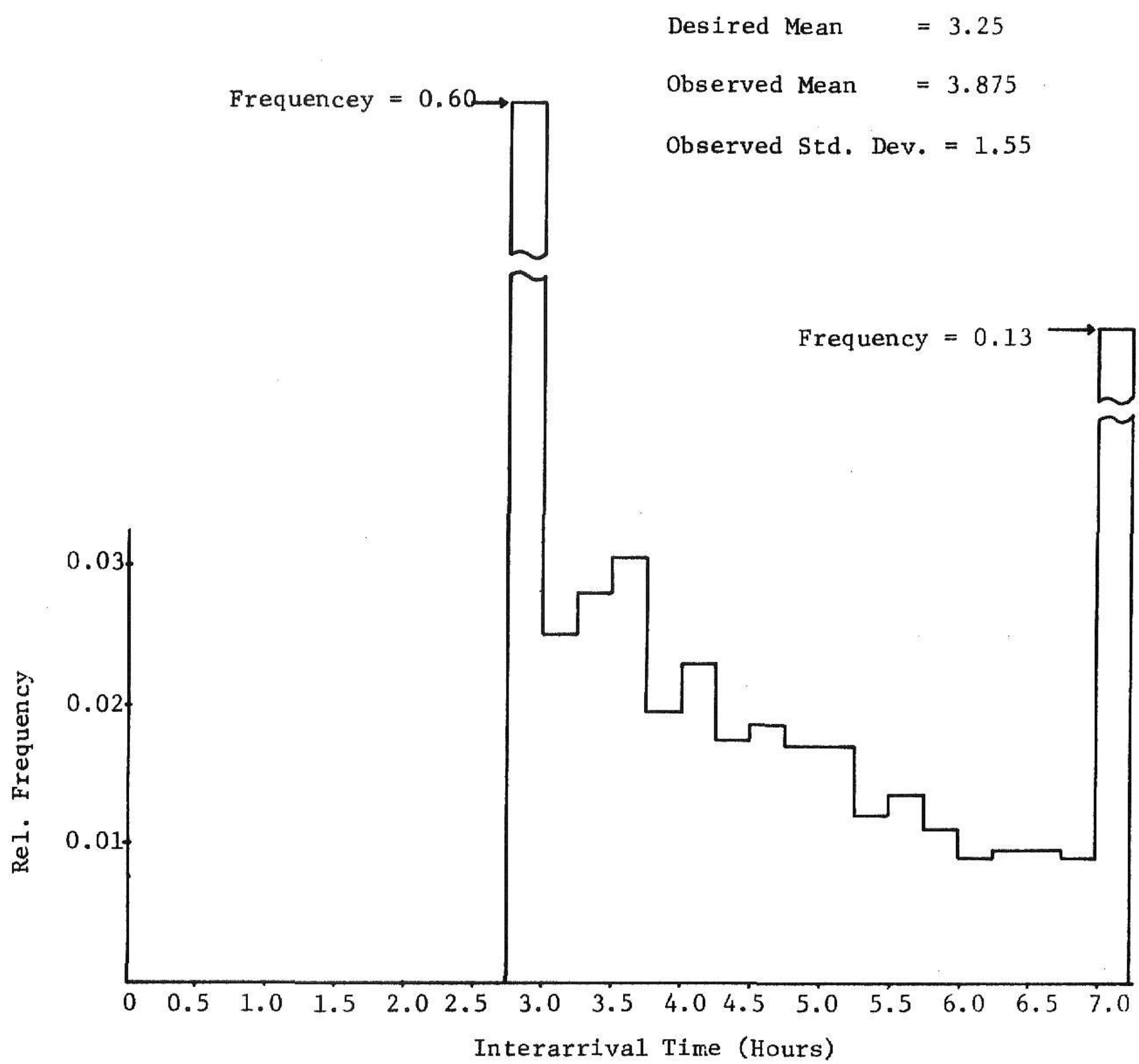

Figure D-1 Relative Frequencies of Generated Interarrival Times for the Truncated Exponential Distribution

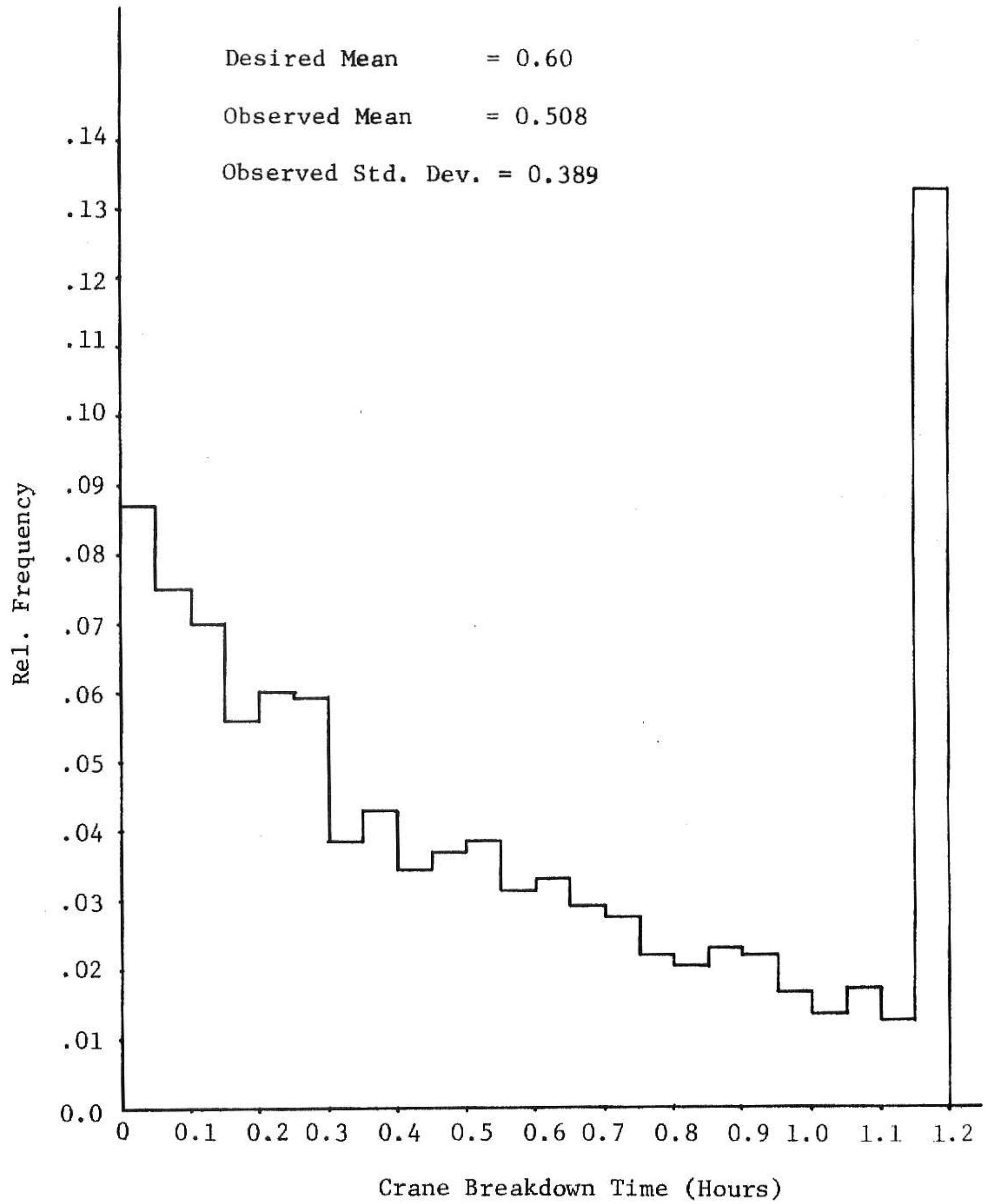

Figure D-2 Relative Frequencies of Generated Crane Breakdown Times for the Truncated Exponential Distribution.

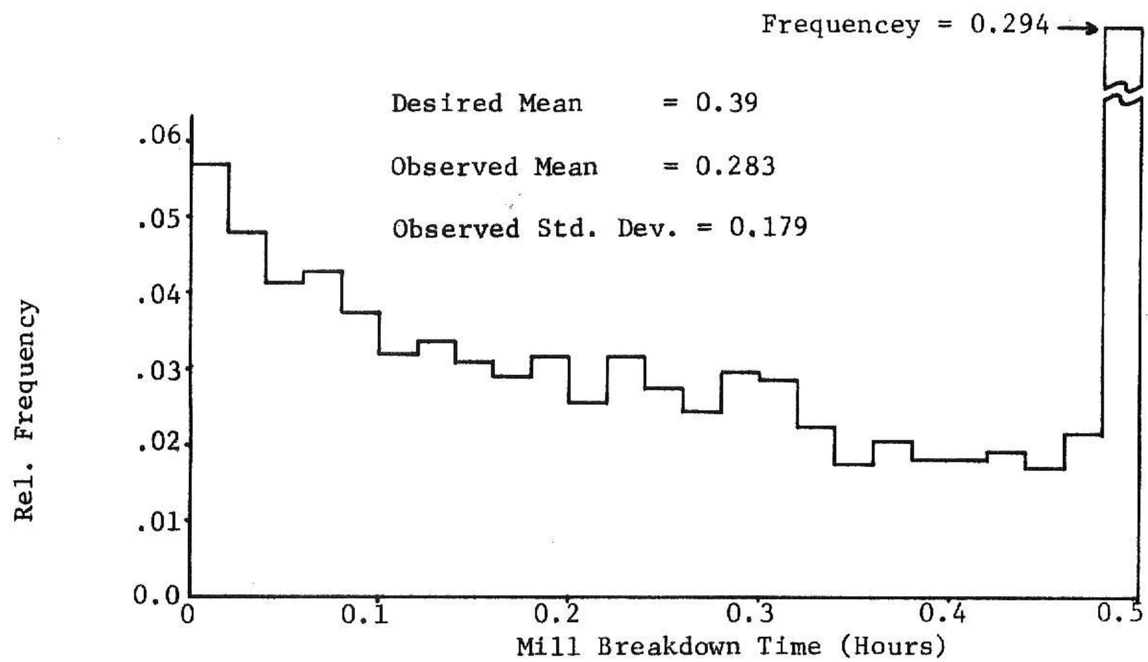

Figure D-3 Relative Frequencies of Generated Mill Breakdown Times for the Truncated Exponential Distribution

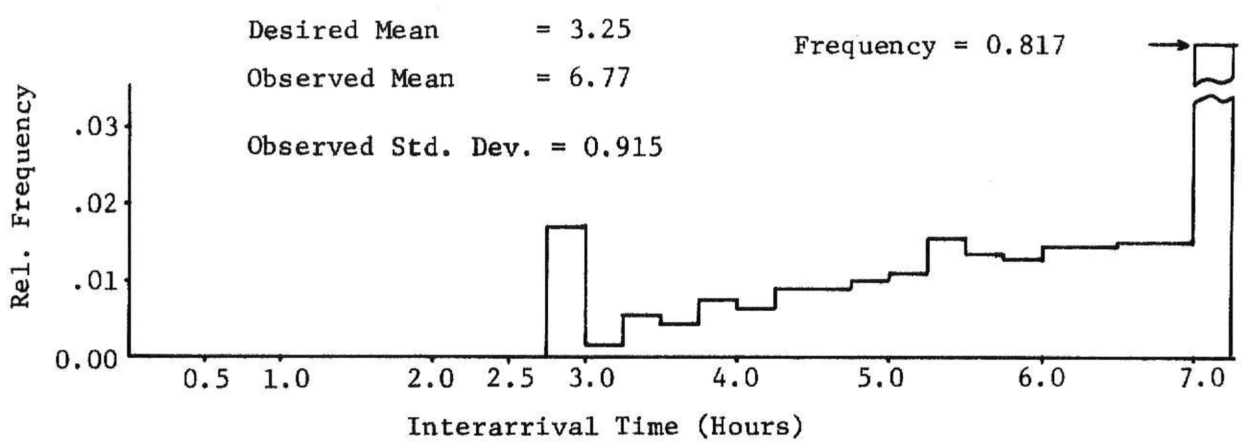

Figure D-4 Relative Frequencies of Generated Interarrival Times for the Truncated Erlang 4 Distribution.

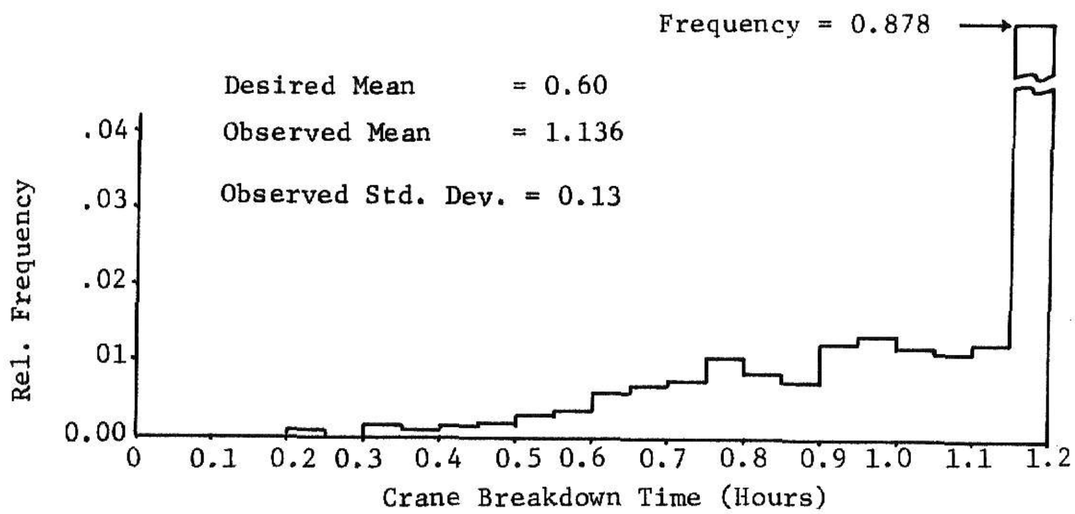

Figure D-5 Relative Frequencies of Generated Crane Breakdown Times for the Truncated Erlang 4 Distribution.

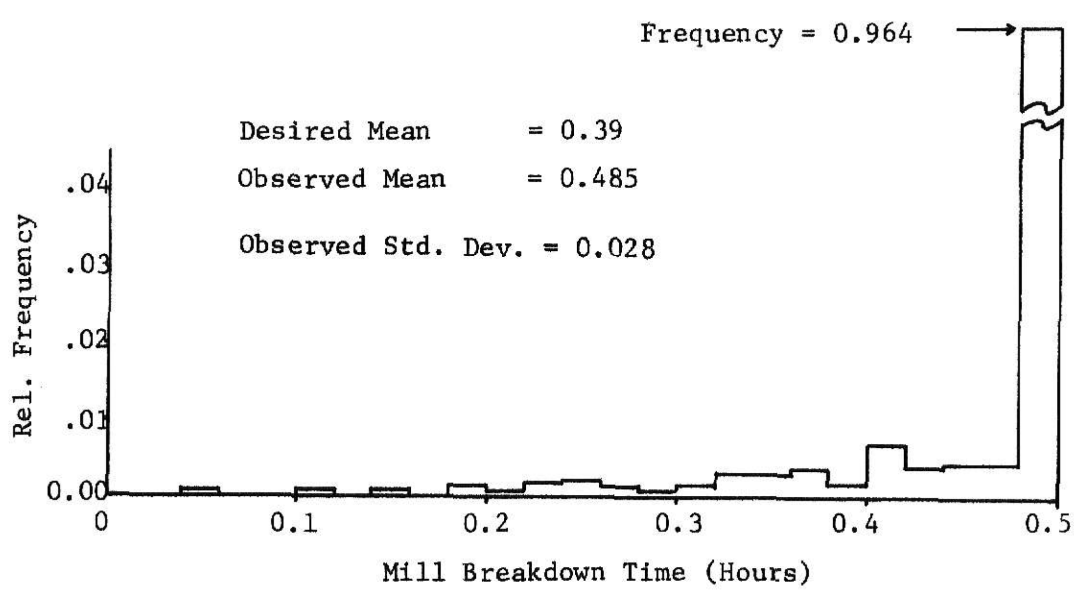

Figure D-6 Relative Frequencies of Generated Mill Breakdown Times for the Truncated Erlang 4 Distribution.

AN OPTIMAL DESIGN OF A SOAKING PIT - ROLLING MILL SYSTEM

by

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B. E. (Mech.), Poona University, India, 1968

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

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1972

ABSTRACT

While attention in the iron and steel industry has been focused on the study and analysis of the flow of materials through the main productive units: blast furnaces, steel work, and rolling mill, the analysis of this flow through the non-productive units: the mixer and soaking pits is overlooked. These two units could create serious bottlenecks in production if their capacities were not properly determined before being installed. This paper considers the soaking pits-rolling mill complex as a queueing system in which the soaking pits, each is charged by a number of ingots, are considered as units circulating a cyclic queue, with the rolling mill as the service station.

An analytical model fitting this system is extracted from a very general cyclic queueing model. However, when overhead cranes are considered as part of the system to charge arriving and cold ingots and draw soaked ingots, the system becomes very difficult to solve analytically, and thus a simulation model is developed to (1) predict the improvement in the system through determining the optimal capacity of the soaking pits-rolling mill complex, and (2) predict the effect of breakdowns and maintenance. The necessary measures of effectiveness including economic aspects are computed. The optimal capacity of the system is determined such that an economic balance between the cost of service and the cost of waiting for that service is achieved. With similar assumptions, both analytical and simulation models are compared to test the validity of the solution.