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A study of a two-stage flowshop with interstage storage as it relates to a structural steel beam rolling mill.

Deborah Louise Halkins

A STUDY OF A TWO-STAGE FLOWSHOP
WITH INTERSTAGE STORAGE
AS IT RELATES
TO A STRUCTURAL STEEL BEAM ROLLING MILL

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A Thesis

Presented to the Graduate Committee

of Lehigh University

in Candidacy for the Degree of

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This thesis is accepted and approved in partial fulfillment of the requirements for the degree of Master of Science.

April 22, 1983
(date)

Professor in Charge

Chairman of Department

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ABSTRACT

The level of production output can be improved for a two-stage flowshop by providing buffer storage between the stages of the line. Controlling the production to achieve maximum output can be enhanced by a decision-making tool that indicates how to efficiently utilize an intermediate storage area with respect to an efficient rolling schedule for a structural steel beam mill. A heuristic procedure, presented by Ignall and Silver, is implemented to determine buffer stock levels. The implementation of Johnson's Rule with start-lags and stop-lags creates the efficient permutation schedule. A Markovian decision process is used to develop a stock depletion policy. The thesis will develop a decision-making tool that utilizes such an approach.

CHAPTER I

INTRODUCTION

Problem Statement

The purpose of this study is to develop a decision-making tool that would indicate how to efficiently utilize an intermediate storage area in conjunction with an efficient production schedule. Theoretical models will be tested in the second chapter to determine the amount of storage needed for various production levels and to depict those levels graphically. The objective is to maximize production output. A scheduling model will be developed in the third chapter for two "machines" in series using flowshop techniques. The objective is to schedule jobs to minimize total cost. The jobs are the various types of steel beams that are produced. These are referred to as "sections." "Job" and "section" will be used interchangeably throughout the text. A stock depletion policy will also be developed in the third chapter.

The preceding chapters will be consolidated into a plan of production control in the fourth chapter. The plan will be developed by first determining the production required for the succeeding section and locating its appropriate buffer level on the graph developed in Chapter Two. While the second stage is down (the Finishing Mill is not working), the intermediate storage area may be stocked only to the buffer level specified. Ensuing sections may be stocked until the second stage is again working.

So, the measure of effectiveness will be the production level, or the steady-state output rate.[1] One way of improving the production rate is to provide buffer stock between the stages of the line. An in-process buffer decouples the production stages and diminishes the forced down time caused by a stage breakdown.[2]

However, inventory always has costs associated with it; that of occupying space, materials handling activities, and work performed from previous stages. The question is how much buffer capacity should be provided.

Discussion of Background Material

In a structural steel mill operation, efficient scheduling of the product can increase throughput (tons per hour), fuel efficiency, mill productivity, and mill yield while reducing total costs, delays, and intermediate inventories. One of the most influential factors is the interfacing that occurs between the operations. Ideal

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[1]Theodore J. Sheskin, "Allocation of Interstage Storage Along An Automatic Production Line," AIIE Transactions, Vol. 8, No. 1, March 1976, p. 146.

[2]K. Okamura and H. Yamashina, "Analysis of the Effect of Buffer Storage Capacity in Transfer Line Systems," AIIE Transactions, June 1977, p. 127.

situations are rare, as a delay or problem in one stage compounds to cause conflicts in the next phase of the process.

A scheduling method, which includes consideration of an intermediate storage area, will be developed to alleviate some of the problems specifically encountered in an actual mill operation. The goal is to keep a steady flow of product throughout the process. Before presenting the mathematical model under consideration, a more detailed account of the physical environment is now rendered.

The product, a steel beam, begins its life as molten metal poured from the Basic Oxygen Furnace's (BOF) ladle into ingot moulds placed on stools. These stools are on buggies that are pulled from the BOF to the soaking pits (reheat furnaces) by narrow gauge engines. One set of ingots poured from one ladle is referred to as a "heat."

The ingots are placed in the soaking pits by overhead cranes. The function of the soaking pits is to reheat the steel to rolling temperature, which is approximately 2440°F. Depending upon the track time, the size of the ingots, and the number of ingots in the soaking pits, the heating and soaking times (the time spent in the soaking pit) will vary. When the ingots are ready to be rolled, that is, they have attained a 2440°F temperature and are soaked throughout, they are then drawn from the soaking pits by cranes and rolled into blooms at the Blooming Mill. The Blooming Mill consists of two stands and is a flowshop, as the product must go from one to the other. This is an ingot-to-bloom process. Since the bloom is an intermediate stage of the product and must be subjected to further processing, intermediate inventories of blooms will occur. Please refer to Figure I for general work flow.

After the bloom leaves the Blooming Mill complex, it continues its trek by roller line to the bloom shears. From the bloom shears, the blooms enter into the Bloom Yard on the high transfer. The blooms are allocated to one of two paths. The first is to remain on the roller line through the Bloom Yard and enter the reheat furnaces for the Finishing Mill. This is an ideal situation. The two mills, the Blooming Mill and the Finishing Mill, have merged into one flow shop.

The ideal situation results in a reduction of costs for material handling and fuel consumption. The blooms have retained latent heat from the previous heating and rolling process, and the blooms never enter the intermediate inventory. Intermediate inventories incur holding costs as well as costs for personnel to catalogue, track, and handle the blooms. The mill complex was initially designed for this ideal situation, for which the term "hot connect" was coined. The Bloom Yard was developed to add

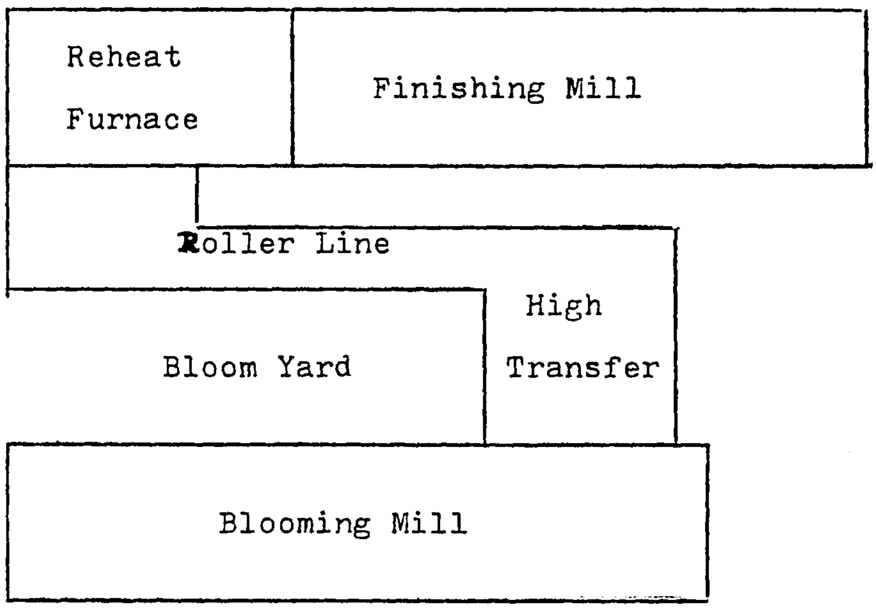

FIGURE I. DRAWING OF MILL COMPLEX

flexibility to the operation and to guarantee continuous operation of the Finishing Mill, the "bloom-to-finish" mill.

The alternate path for the blooms emerging from the bloom shears is to be taken off the roller line and stocked on the skids in the Bloom Yard. This is convenient if the section being rolled on the Blooming Mill is to be rolled on the Finishing Mill several days later. It is safer to roll a certain percentage of the section ahead of the Finishing Mill's rolling schedule so that the mill will not stop operating because of a "no stock" condition, thus ending the dependency of the Finishing Mill upon the Blooming Mill. In this manner, if the Blooming Mill is experiencing difficulties and is unable to roll while the problem is being corrected, the Finishing Mill can begin rolling the section and experience no delays attributable to the preceding mill. When the problems are corrected, the Blooming Mill would then affect the "hot connect" condition so desirable to the operation.

To complete the picture, a short discussion of the Finishing Mill is in order. The two reheat furnaces receive blooms from the Bloom Yard roller line. The order in which the blooms are placed on the roller line dictates the order in which they are received at the furnaces. The number of furnaces used is dependent upon the section being rolled.

As the blooms are released from the furnaces, they are rolled at 4 consecutive stands. The Breakdown Mill performs 5 to 7 passes on the blooms. The Roughing Mill consists of the main mill and the edging mill. The normal practice is 3 passes at this point. The Intermediate Mill consists of the main mill and the edging mill. The practice at this point is also 3 passes. The Finishing Mill performs one pass on the beam. The four mills constitute a flowshop process. The beams, now approximately 250 feet long, leave the Finishing Mill and are transported by walking beam cooling beds (north and south). The beams are cooled on the beds to lower temperatures by being shifted gradually to the rotary straighteners. After passing through the rotary straighteners, the beams are inspected and cut to customer order lengths at one of the four cold saws. They are moved by cranes and stored or loaded for shipment. The design of this mill was for a rate of a "beam a minute."

Assumptions of the System's Characteristics

In reviewing the available literature, several theories were presented that address the two-stage system with intermediate storage. Very few applications of the theories were presented. This study will contribute to the testing and validating of these theories.

First, it becomes necessary to properly define the conditions and terms of the storage problem. In this particular case:

first production stage = Blooming Mill

intermediate storage or buffer = Bloom Yard

second production stage = Finishing Mill

There are four possible conditions that can exist for the system. Let:

$P(S_1, S_2)$ = Probability (state of stage 1, state of stage 2)

where a state is either U = up or operating or it is D = down or not operating. Then:

Condition	$P(S_1, S_2)$	Status
1	P(U,U)	both stages are working
2	P(U,D)	stage 1 is working, stage 2 is not; stage 1 is stocking blooms in the buffer
3	P(D,U)	stage 1 is not working, stage 2 is; stage 2 is drawing blooms from the buffer
4	P(D,D)	both stage 1 and stage 2 are down; no activity

Certain assumptions are made in this study and are listed below:

1. Ingots enter the production line at stage 1.
   Reasoning: Ingots are placed in the soaking pits for reheating before they are rolled at the Blooming Mill

(that is, stage 1). All ingots must pass through the soaking pits before being rolled.

2. The stages are arranged serially.

   Reasoning: The blooms flow from the pits to the Blooming Mill to the Finishing Mill as demanded by the technological process.

3. There will always be facilities to accept the output from stage 2.

   Reasoning: Beams leaving the Finishing Mill are cycled by cooling beds to rotary straighteners and to cold saws. Beams may cycle either north or south, and the facilities on one side mirror those on the other. (Hence, if one side is down, the other can handle the output.)

4. There is an infinite supply of ingots.

   Reasoning: Because there are 4 batteries of pits to service stage 1, it is assumed that proper scheduling at the pits will ensure an infinite supply of ingots.

5. The output, in the form of blooms, from stage 1, feeds one buffer area.

   Reasoning: The output feeds the Finishing Mill.

6. The problem is being viewed as a two-stage line with one "machine" in each stage.

   Reasoning: (Ignall. [10], p. 187) states that the results are similar for the two-stage lines and lines with several machines per stage. The two-stage line problem is more manageable.

7. The "machines" produce at a fixed rate.

   Reasoning: The Finishing Mill produces a "bar a minute," which equates to 60 bars per hour. The Blooming Mill rolls 121.03 ingots per shift. This equal to 15.129 ingots per hour. At 4 cuts per ingot, this is equal to 60.52 bars per hour.

8. The times between failures and the repair times are exponentially distributed.

   Reasoning: Please refer to the graphs of times for both mills in Figures II and III.

9. There are no end-of-shift or beginning-of-shift adjustments.

   Reasoning: The operation is a continuous one, so there is no chance to run overtime to "catch up" with the work.

10. Planned downtime for maintenance and preventative maintenance is not included in this analysis.

    Reasoning: Preventative maintenance and maintenance are performed either on a scheduled repair shift or while the mills are rolling.

11. Machines fail independently of each other.

    Reasoning: The "machines," when referring to the Blooming Mill and the Finishing Mill, are separate mill complexes and do fail independently of one

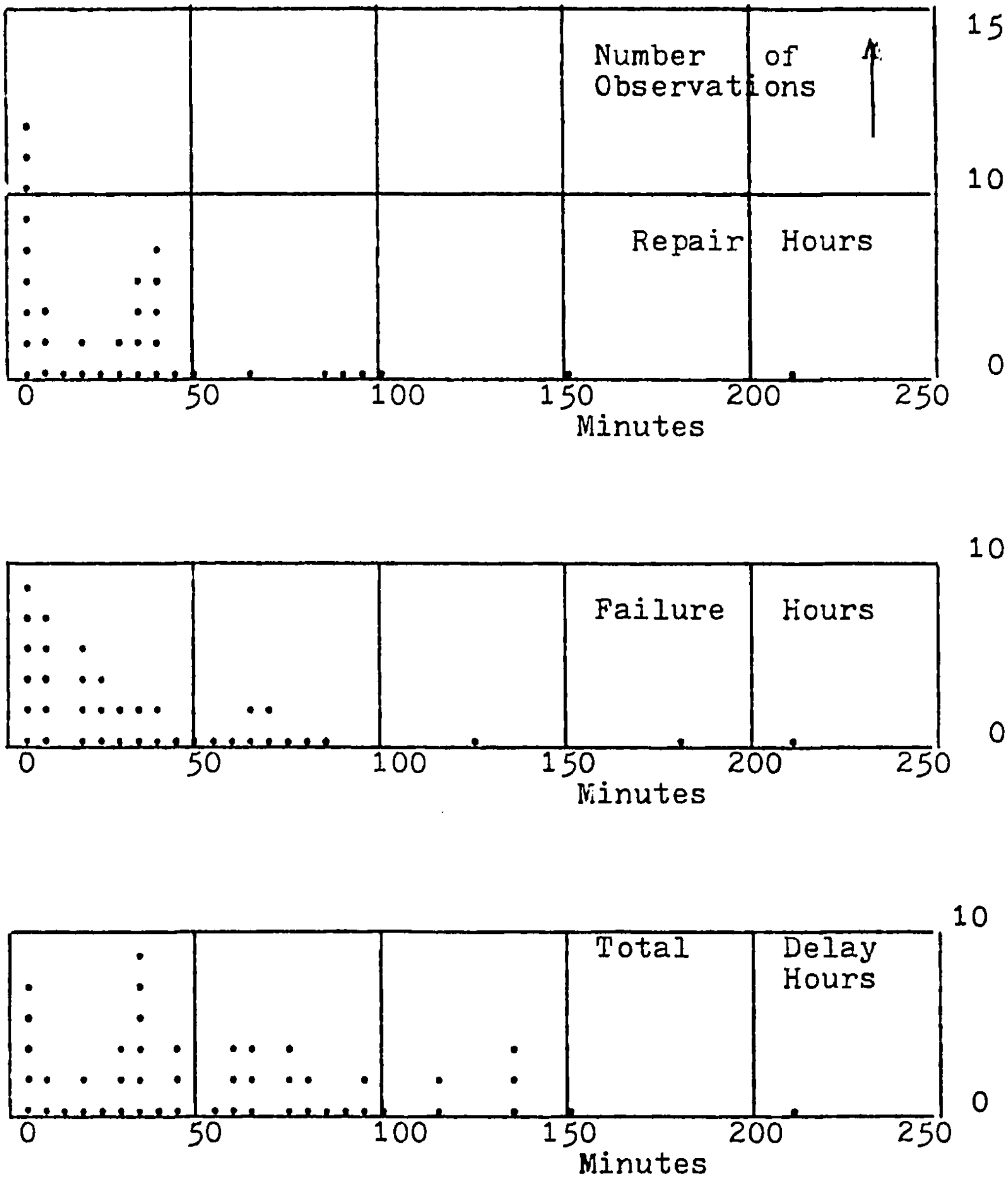

FIGURE II. BLOOMING MILL:

HISTOGRAM OF DELAY HOURS

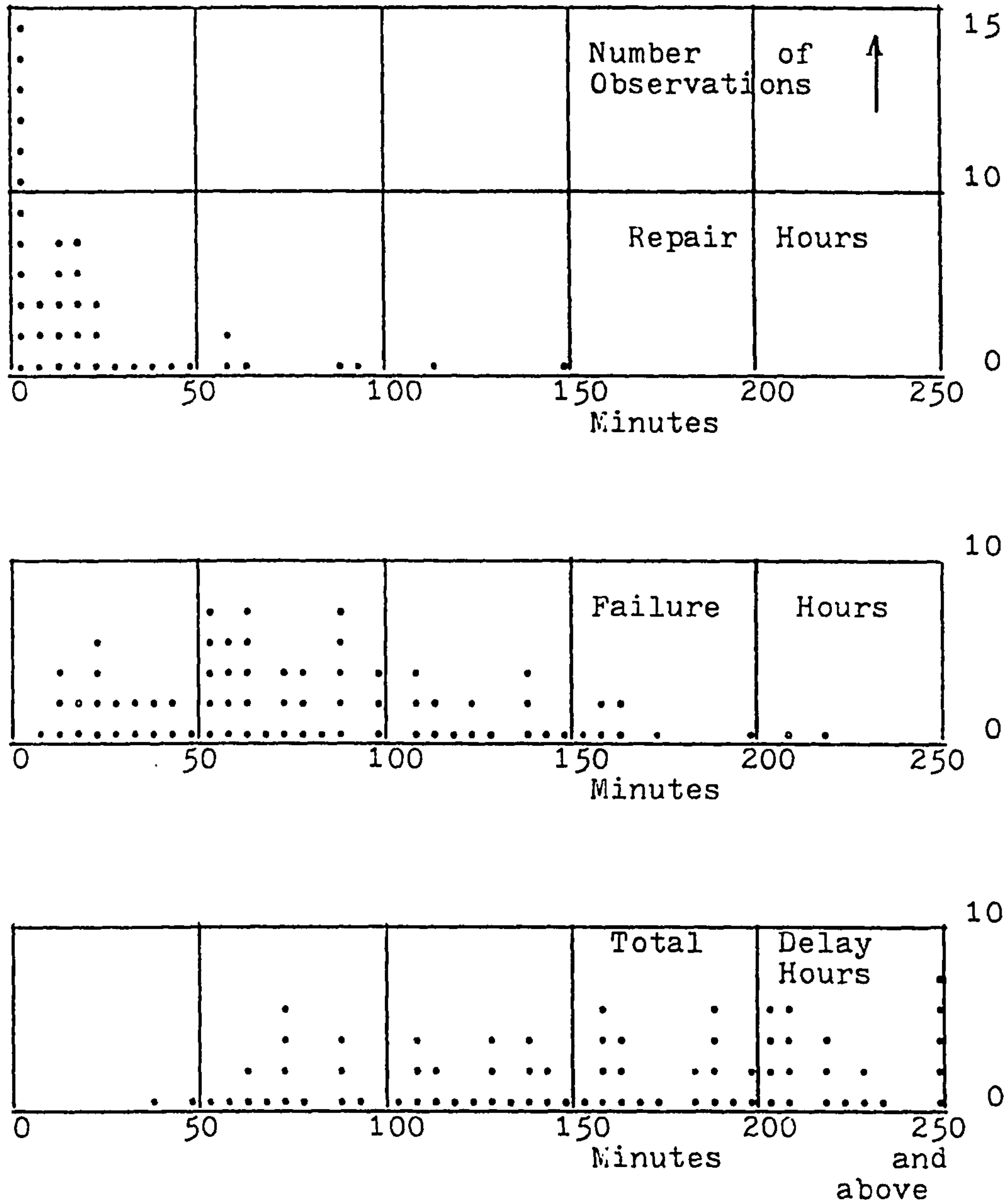

FIGURE III. FINISHING MILL:

HISTOGRAM OF DELAY HOURS

another. However, within each complex, the machines may not fail independently. An example of this is a rejected bar that occurs at the Intermediate Mill where the bar extends to the Finishing Mill. (The metal is being worked too hard.) This aspect is not a problem in this study because a mill complex cannot roll at any of the mills unless all mills are rolling. So, the mill complexes are the "machines."

12. A machine that is blocked or starved cannot fail. Reasoning: If the machine is not working, it is in an idle state and is considered to be incapable of failing while not performing. If the work becomes available, the machine is ready to receive the work from its idle state.

13. Transport time between stages is assumed to be subsumed by unit production times.[3] Reasoning: The definition of unit production times as specified by the model chosen for application will address transport time.

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[3]*Ibid*, p. 128.

CHAPTER II

INTERMEDIATE BUFFER CAPACITY

Literature Review and Model Selection

A literature review uncovered many articles that addressed the intermediate buffer problem. Most of these articles were theoretical approaches with little or no actual applications. Most of them used some sort of simulation model and drew their conclusions from the results. The main thrust of most of the articles was to determine if a buffer should be included in an automatic production line. Almost all of the articles reviewed made reference in one way or another to Ernest Koenigsberg's article [11]. Since this is the case, the perfect place to begin the review is with this article.

Terminology that was common throughout a majority of the articles can be found in Koenigsberg [11]. This same terminology is used in this study as well. Koenigsberg discusses 4 approaches: the simple or naive approach, the loss transfer method, the stochastic model, and the queue model. He compares the approaches and concludes that the more sophisticated methods yield results that mirror those of the naive, simple approach. This approach is, indeed, simple. Given that:

p_1 = fraction of downtime on machine one.

p_2 = fraction of downtime on machine two.

R = output expressed as a fraction of the maximum possible output.

For a no-buffer situation:

$$R \text{ (no buffer)} = 1 - p_1 - p_2 + p_1 p_2$$

Suppose $p_1 = .20$ and $p_2 = .30$.

Then $R = 1 - .2 - .3 + (.2)(.3) = 0.506$

So, the output is 50.6% of the maximum possible output.

For an infinite-buffer situation:

$$R \text{ (infinite buffer)} = 1 - p$$

where p = fraction of downtime at its worse stage.

Suppose p = .3

then R = 1 - .3 = 0.70

So, the output is 70.0% of the maximum possible output. The application of an infinite buffer area has increased output by .7 - .506 = .194 or 19.4%. At 60 bars per hour 60 (.194) = 11.64 bars per hour increase. All finite buffer sizes fall within an output range of 50.6% to 70.0% of maximum.

The loss transfer method is touched on briefly by (Koenigberg, [11], p. 415). The model is a work by Vladziyevsky [16]. His definition of the problem is "to determine to what extent the productivity of an automatic line depends on its separation into a larger or smaller number of successive sections, connected to each other by 'bunker' devices which store semi-manufactured products."[1] Koenigsberg lists several reasons why he does not agree with the model, one of which is that Vladziyevsky does not consider in his problem definition the requirements for storage space in the forward direction to allow output from the previous stages to be stored when the succeeding stage is down. Stocking blooms is an important factor in this study.

The stochastic model from Finch [8], is a study of storage problems in a line of continuous flow. It includes the effects of stoppages due to breakdowns and settings, and is not restricted to the assumption of a balanced line. Let:

$l(i) = \frac{1}{\lambda(i)}$ = mean working time duration of machine i

$m(i) = \frac{1}{\mu(i)}$ = mean down time of machine i

$\frac{1}{k(i)}$ = work cycle time or process time of machine i

The work cycle time is assumed constant.

Continuing,

N = expected number of units in the buffer when the system is in equilibrium.

g(k) = output during the kth state.

He ultimately derives this equation:

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[1] Ernest Koenigsberg, "Production Lines and Internal Storage-A Review," Management Science, Vol. 5, 1945, p. 416.

$$G(N) = U\ 1 - \frac{(1-U)(\mu(1)+\mu(2))\,h}{h(1+U)(\mu(1)+\mu(2))+N(\mu(1)+U\mu(2))(\mu(3)+U\mu(1))}$$

However, in the limits ($N \to 0$ and $N \to \infty$) the results can be shown to be identical to the naive view discussed at the beginning of the paper (substitute $p^i = m_0/(m_i + l_i)$).

For the queue model, if it is assumed that the production line is a tandem servicing system, each section of which providing "service" at a mean rate μ and that the service time has an exponential distribution, then it is a queueing system. This is not the situation that exists in the mills.

So, from Koenigsberg's work, it appears that Finch's stochastic model most nearly represents the problem addressed, and that the results from Finch's model are identical to those of the simple, naive view.

Wijngaard [18] locates regeneration points in the system, such as the points in time when the buffer becomes empty. The time between two subsequent regenerations is called a cycle. The output rate of the production line can be written as:

Rate = expected production per cycle
divided by the expected duration of a
cycle.

The buffer in this study does not become empty of a section until the job is completed. This limits the use of the regeneration approach, as there would only be one regeneration point.

Wijngaard notes in his analysis that "the more the line is unbalanced, the less buffer capacity is needed. The difference in the production rates (unbalanced line) can be caused by a difference in failure rate, a difference in repair rate, or a difference in production rate."[2]

Koenigsberg's work supports an article by Michael Freeman [7]. "The basis for choosing the exponential model is the empirical evidence that actual production facilities behave in that manner. Such evidence is cited in Koenigsberg."[3] In the model to be applied to the problem, the failure and repair times are also chosen to be exponential because of this reference and the analysis of actual data.

Freeman [7] assumes that the buffers are not preloaded with parts at the beginning of the production run. In the cases being studied, this is not always the rule. In most situations, the section being rolled is partially "cut out" ahead of the scheduled rolling time.

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[2]J. Wijngaard, "The Effect of Interstage Buffer Storage on the Output of Two Unreliable Production Units in Series, With Different Production Rates." AIIE Transactions, Vol. 11, No. 1, 1979, p. 45.

[3]Michael C. Freeman, "The Effects of Breakdowns and Interstage Storage on Production Line Capacity," The Journal of Industrial Engineering, Vol. 15, No. 4, p. 195.

Freeman created a computer simulator for a 3-stage automated line based on Finch's work. Freeman also presents a measure of effectiveness. Let:

P_d = percent of time the line is down for a given alternative

$P_d(0)$ = percent of time the line is down if zero storage capacity is provided

$P_d(\infty)$ = percent of time the line is down if infinite storage capacity is provided

Then the measure of production efficiency, E, is:

$$E = \frac{P_d(0) - P_d}{P_d(0) - P_d(\infty)}.$$

Application of Model

The model that was chosen for application to the problem was taken from Edward Ignall and Alvin Silver [10]. They presented a method for estimating the average hourly input of a two-stage production system as a function of how much buffer capacity is provided between the stages.

The assumptions listed in Chapter I of this report matches theirs. The terms used to describe the model are listed below:

α_j = failure rate of the machine at stage j

$1/\alpha_j$ = mean time before failure at stage j (MTBF)

βj = repair rate at stage j

$1/\beta j$ = mean time to repair at stage j (MTTR)

R_0 = output rate when there is no buffer storage

R_∞ = output rate when buffer storage is infinite

k = production rate of each machine, when up and running.

They specify that all quantities should be in compatible time units. This means that all figures are in hours or all are in minutes, but not a combination of the two. Their suggestion is to let the cycle time of the machines dictate the time unit.

The formulas they develop are quoted below:

$$R_O = \frac{k}{1 + (\alpha_1/\beta_1) + (\alpha_2/\beta_2)}$$

$$R_\infty = k/\left(1 + \max\left(\frac{\alpha_1}{\beta_1}, \frac{\alpha_2}{\beta_2}\right)\right)$$

For a given amount of storage, z, Ignall and Silver suggest:

$$R(z) = R_O + (R_\infty - R_O)\, m(z)$$

where m(z) is a weighting factor, with m(O) = O and m (∞) = 1, and m(z) increases as z increases.

The summary on p. 187 of their article reduces the method to three steps:

1. Compute R_∞.
2. Compute R_O.
3. Compute R(z).

Using the equations for R(z) for various buffer levels, z, the rate of output is determined. A graph can then be developed to aid in decision-making, which would appear as a plot of production rate versus buffer level.

Ignall and Silver convert several machines at each stage to a single machine at each stage. In this case, the Blooming Mill complex will be viewed as one stage and the Finishing Mill will be viewed as the second stage. The first step in the application of the model is data collection and analyis. Please refer to Appendices I and II for the data tables. Data collection for Stage 1 (Blooming Mill) revealed the following:

Total hours =	453.80	
Total Number of Shifts =	60.0	
Failure hours =	32.583	
Repair hours =	30.1667	
Roll change & section hours	0.417	
Number of ingots/shifts	121.03	
Number of ingots/hour =	15.13	
Equivalent number of blooms/hour =	60.52	(15.13 x 4*)

* 4 = average number of blooms/ingot

Data collection for stage 2 (Finishing Mill) revealed the following:

Total hours =	588.40
Total number of shifts=	75.0
Failure hours =	103.08

Repair hours =	17.75
Roll change and section hours=	72.833
Number of blooms/shift =	322.27
Number of blooms/hour =	40.28
Ideal number of blooms/hour	60.0

Failure hours include time for cobbles, nothing hot (in the soaking pits or in the reheat furnaces), cooling beds blocked, a no-stock condition, and other miscellaneous problems. Repair hours are either mechanical or electrical delays related to equipment failure. Failure hours and repair hours are two different and separate delay categories. Machine failure as defined by Ignall and Silver is the repair hours plus the failure hours.

Continuing analysis with the model, the cycle time must be defined. If the cycle time is for the entire mill system, then it would be "a bar a minute." So, the time unit to be employed is one minute, and $k = 1$. The mean time to repair would then be the average number of the one-minute cycles in a repair.

Every actual system has its limitations, and the buffer capacity in the Bloom Yard depends on many factors, including the scheduling rules used at any point in time and the nature of the section being rolled. It is therefore necessary to calculate the output rate for varying levels of buffer capacity, R(z), where "R" is the output rate and "z" is the buffer level.

The weighting factor, m(z), was mentioned earlier and will be defined at this point so that R(z) may be assessed. Ignall and Silver (p. 184) draw upon the work of Buzacott [3], for developing the weighting factor.

Their development of m(z) is given by:

$$m(z) = \max(F,1) \times \frac{1 - Fgz\beta}{1 - F(gz\beta + 1)} \qquad \text{if } \alpha_1 \neq \alpha_2$$

where $g = 1/2\ (1 + \sigma\beta)$

$$\beta = \frac{\alpha_1 + \alpha_2}{\alpha_1/\beta_1 + \alpha_2/\beta_2}$$

$$F = \alpha_1/\alpha_2$$

$$\sigma = \frac{(\alpha_1\alpha_2(1/\beta_1 - 1/\beta_2)^2 + (\alpha_1 + \alpha_2)(\alpha_1\sigma_1^2 + \alpha_2\sigma_2^2))^{1/2}}{(\alpha_1 + \alpha_2)}$$

σ = standard deviation of the system's repair times.

To obtain σ_1 and σ_2, the equation for sample standard deviation, S, is used:

$$S = \left(n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2 / n(n-1)\right).$$

σ_1 = 42.474 minutes and σ_2 = 31.333 minutes.

Applying the presented equations to the data base should reveal the system's characteristics.

Suppose:

Time to repair = failure hours + repair hours

Operating time = total hours - time to repair

Mean time before failure = MTBF = operating time/ number of repairs during total hours.

All times are those occurring during the total hours.

Table I

Data for Buffer Capacity Model

	Stage 1	Stage 2
Total hours	453.80	588.40
Time down	62.7497	120.83
Operating hours	391.05	467.57
Average minutes between repairs (= MTBF)	130.35 min	93.514 min
Average number of delays/shift	3	4
Number of repairs*	180	300
αi	.0077	.0107
% hours in repair	.1383	.2054
Hours/delay**	.3688	.4108
Mean Time to repair (= MTTR)	22.128	24.648
βi	.0452	.0406
$\alpha i/\beta i$	.1704	.2635
Number of shifts	60.0	75.0

*Number of repairs = # shifts x average # delays/shift.

**Based upon the averages of 3 delays/shift for stage 1 and 4 delays/shift for stage 2.

Table I is a summary of the collected and calculated data.

Then

$$R(O) = \frac{1}{1 + (.1704) + (.2635)} = .6974$$

$$R(\infty) = \frac{1}{1 + \max\,(.1704, .2635)} = .7915$$

One can expect 79.15% output level of production capability. At 60 bars per hour, the maximum achievable level of production is .7915 (60) = 47.49 bars per hour.

$$R(\infty) - R(O) = .0941$$

An increase of 9.41% in output can be enjoyed when an infinite buffer is supplied.

.0941 (480 bars/shift) = 45.168 bars/shift increase in output.

Within 11 shifts, at the increased output level, the equivalent of an extra shift will have been added to the schedule (496.848 additional bars).

Supporting calculations for the values on page 24 are presented below.

$$a = (\alpha_1, \alpha_2(1/\beta_1 - 1/\beta_2)^2 = 0.0005$$

$$b = (\alpha_1 + \alpha_2)(\alpha_1, \sigma_1^2 + \alpha_2 \sigma_2^2) = 0.4489$$

$$c = (\alpha_1 + \alpha_2) = 0.0184$$

$$\sigma = \left[\frac{a + b}{c}\right]^{1/2} = \frac{.6704}{.0184} = 36.434$$

$$\sigma = \frac{.6704}{.0184} = 36.434$$

$\beta = \frac{.0077 + .0107}{.1704 + .2653} = \frac{.0184}{.4339} = .0424$

$g = 1/2(1 + (.0424)(36.434)) = 1.2724$

$F = \alpha 1/\alpha 2 = \frac{.0077}{.0107} = .7196$

$g = .0539$

Recalling that

$$R(z) = R_O + (R_\infty - R_O)m(z)$$

$$R(z) = .6974 + .0941\ m(z)$$

$$m(z) = \max(.7196,\ 1)\ \frac{1-(.7196)^{.0539z}}{1-(.7196)^{.0539z}+1} \quad \text{if } \alpha_1 \neq \alpha_2$$

Several examples:

(1.) m(z) = m(60) = .8713

R(z) = R(60) = .7794

(2.) m(100) = .9458

R(100) = .7864

(3.) m(200) = .9918

R(200) = .7907

By looking at various levels of buffer capacity, z, a curve is developed. The data that must be input into the system includes:

Direct	Calculated	Variable
$\alpha 1, \alpha 2$	β, g	z
$\beta 1, \beta 2$	σ, F	
$\sigma 1, \sigma 2$	m(z), R(z)	
R_O, R_∞		

A program to calculate R(z) given a z storage value is easily developed for the HP33E hand-held programmable calculator. Because of the desire to have the tool available on the shop floor, portability and availability is accomplished by the use of a hand-held calculator. If the parameters of the model change, then it is necessary to recalculate g, β, F, R_∞, and R_0. The program is inherently limited in scope because of the number of steps allowed in programming the calculator. Those changes occur at the following steps: (Please refer to the program presented in Table II, and to the calculated values in Table III.

Step Numbers	Input
02 - 06	$(g \cdot \beta)$
12 - 16	F
38 - 42	$(R_\infty - R_0)$
44 - 48	R_0

The use of the program follows these steps:

1. Key in the value of z
2. Run the program
3. Check the values

   To display the values:

   R(z) is in the display

   m(z): key in "RCL 0"

   z : key in "RCL 1"

4. Expected production = R(z) x average production level

Table II

Hewlett-Packard Program for Calculating Data Points

HP program to calculate R(z) given z storage:

	INPUT	STEP#	KEY POSITION
	sto 1	01	23 01
$g \cdot \beta$	.0539	02-06	73, #s
	x	07	61
	sto 2	08	23 02
	1	09	01
	+	10	51
	sto 3	11	23 03
F	.7196	12-16	73, #s
	sto 4	17	23 04
	rcl 3	18	24 03
	f y^x	19	14 03
	sto 5	20	23 05
	rcl 4	21	24 04
	rcl 2	22	24 02
	f y^x	23	14 03
	sto 6	24	23 06
	1	25	01
	ent	26	31
	rcl 6	27	24 06
	-	28	41
	sto 7	29	23 07
	1	30	01
	rcl 5	31	24 05
	-	32	41
	sto 0	33	23 0
	rcl 7	34	24 07
	rcl 0	35	24 0
	-	36	71
	sto 0	37	23 0
$R_\infty - R_o$	.0941	38-42	73, #s
	x	43	61
R_o	.6974	44-48	73, #s
	+	49	51

Table III

Example Curve Data Points

Utilizing the program, the following values were calculated:

z	m(z)	R(z)
0	0	.6974
10	.4090	.7359
20	.6029	.7541
30	.7147	.7647
40	.7865	.7714
50	.8358	.7760
60	.8713	.7794
70	.8977	.7819
80	.9178	.7838
90	.9935	.7852
100	.9458	.7864
120	.9635	.7881
140	.9751	.7892
160	.9829	.7899
180	.9881	.7907
200	.9918	.7910
220	.9943	.7911
240	.9960	.7911
260	.9972	.7912
280	.9980	.7913
300	.9986	.7914
320	.9990	.7914
340	.9993	.7914
360	.9995	.7915
380	.9997	.7915
400	.9998	.7915
420	.9998	.7915
440	.9999	.7915
460	.9999	.7915
480	.9999	.7915
500	1.0000	.7915

Suppose the operations differ substantially. The values in Table IV have been used as an example to develop general trends.

Table IV

Data for a Second Curve

Variable	Stage I	Stage II
MTBFi	140	80
αi	.0071	.0125
MTTRi	20	35
βi	.0500	.0286
$\alpha i/\beta i$	.1420	.0437
σi	45	25

Then $\sigma = 34.4085$

$\beta = 0.1055$

$g = 2.3158$

$F = 0.55680$

$g \cdot \beta = 0.2443$

$R_O = 0.8434$

$R_\infty = 0.8757$

$R_\infty - R_O = 0.8757 - 0.8434 = 0.0323$

Suppose both the mean time before failure and the mean time to repair for the two stages are not similar in their duration. The following values were calculated and appear in Table V.

Table V

Example Curve Data Points for the Second Curve

z	m(z)	R(z)
0	0	.8434
10	.8735	.8716
20	.9717	.8748
30	.9931	.8755
40	.9983	.8756
50	.9996	.8757
60	.9999	.8757
70	1.0000	.8757
80	"	"
.	.	.
.	.	.

Suppose the operations are more uniform in mean times. As an example, the values in Table VI have been used to develop general trends:

Table VI

Data for a Third Curve

Variable	Stage I	Stage II
$MTBF_i$	120	105
α_i	.0083	.0095
$MTTR_i$	23	23.5
β_i	.0435	.0426
α_i/β_i	.1908	.2230
σ_i	30.0	30.0

Then

$$\sigma = 30.0023$$

$$\beta = 0.043$$

$$g = 1.145$$

$$F = 0.8737$$

$$g \cdot \beta = 0.0492$$

$$R_O = 0.7073$$

$$R_\infty = 0.8177$$

$$R_\infty - R_O = 0.1104$$

Utilizing the program for the more uniform operation, the following values were calculated and appear in Table VII.

Table VII

Example Curve Data Points for a Third Curve

z	m(z)	R(z)
0	0	.7073
10	.3523	.7462
20	.5294	.7657
30	.6358	.7775
40	.7067	.7853
50	.7572	.7909
60	.7950	.7951
70	.8242	.7983
80	.8474	.8009
90	.8663	.8029
100	.8819	.8047
120	.9061	.8073
140	.9240	.8093
160	.9375	.8108
180	.9481	.8120
200	.9565	.8129
220	.9633	.8136
240	.9688	.8143
260	.9734	.8148
280	.9772	.8152
300	.9805	.8155
320	.9832	.8158
340	.9855	.8161
360	.9874	.8163
380	.9891	.8165
400	.9906	.8167
500	.9953	.8172
600	.9976	.8174
700	.9988	.8176
800	.9994	.8176
900	.9997	.8177
1000	.9998	.8177
1100	.9999	.8177
1200	1.0000	.8177

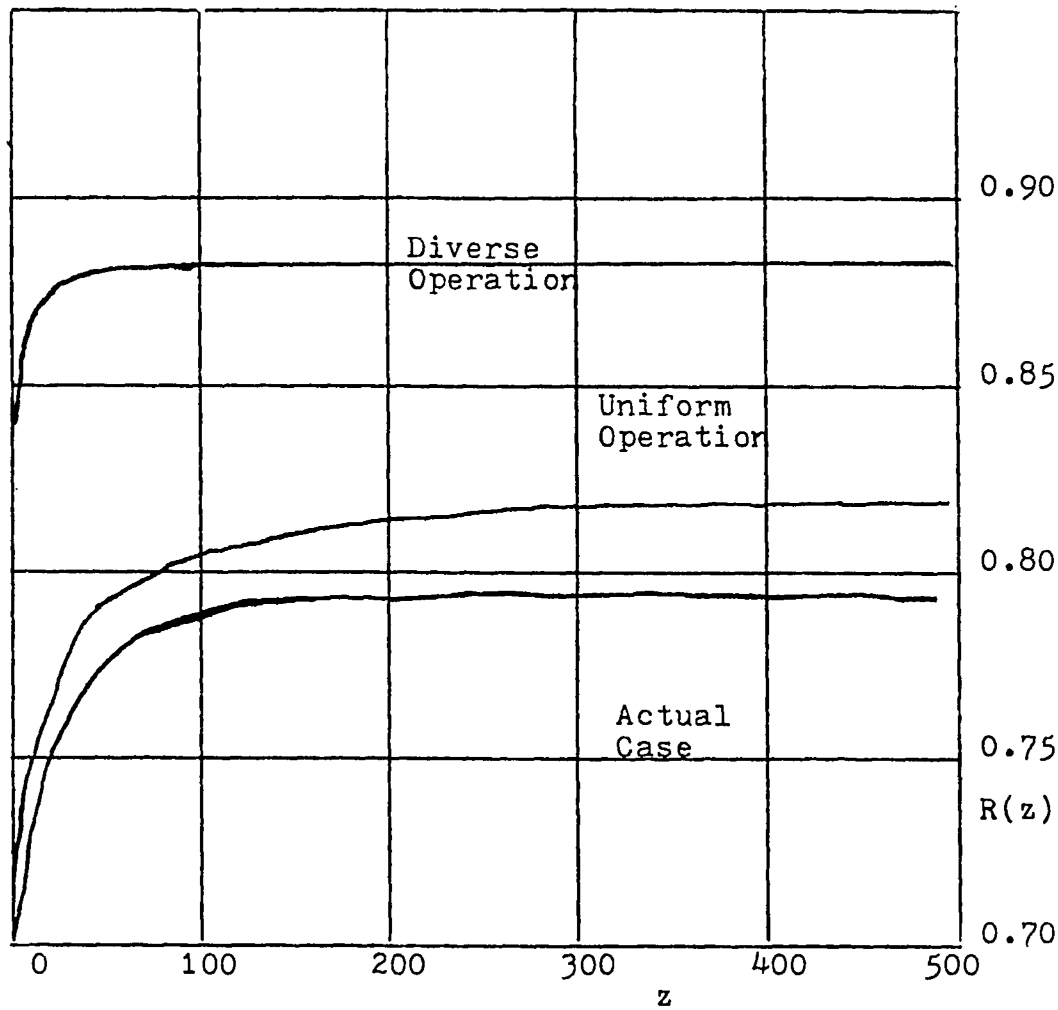


FIGURE IV. PRODUCTION RATE VERSUS BUFFER LEVEL

Results

Observations of the actual data show that any value of z above 200 bars adds little to the output rate. The most drastic step-wise changes in the output rate occur at the lower values of z.

The approach appears to be an interpolation problem encased between two limits.

The curve developed a sharp upward trend for the lower values of z and tapered off to a horizontal line at a level of z = 200 bars. When no buffer is supplied, any delay on the Blooming Mill results in downtime for the Finishing Mill. With the addition of 10 blooms in stock, the Finishing Mill can continue to run for 10 minutes from the start of the delay on the Blooming Mill. That additional time may even span the entire delay, thus maintaining the output rate for the finished mill. As the buffer tends to infinity, the beneficial effect is lessened because the additional stock is not used to combat the delays.

Between z = 100 and z = 200, the gain in the output rate is small, 0.7910 - .7864 = 0.0036. Because of the costs of stocking, the slight increase in output does not outweigh the costs. One would then not be as inclined to stock above 100 bars, but would prefer to stock somewhere above zero and less than or equal to 100.

The curves for the diverse operation and the uniform operation were at higher output ranges. With the operation whose stages vastly differed, the output increases rapidly initially and tapers off to the maximum output rate at $z = 40$. In a more uniform case, the output rate reaches its maximum at a slower rate. The value of R at $z = 200$ is close to R_∞, and at $z = 300$, the additional output to reach R_∞ is 0.8177 - 0.8155 = 0.0022.

CHAPTER III

SCHEDULING PROCESS

Literature Review and Model Selection

The optimal scheduling of the jobs to be completed on the Blooming Mill and the succeeding Finishing Mill illustrates the case of a flowshop using two machines in series. In this particular case, the jobs can be started on "machine two" before "machine one" has completed its work on the job.

Part II discusses the determination of a maximum possible output rate taking into account an intermediate buffer area and the inherent operating characteristics of the two-stage system. Supplying an optimally sequenced set of jobs allows for a maximum return from the system.

A literature review of possible scheduling methods pointed to articles such as E. L. Lawler and J. M. Moore's article [12], "A Functional Equation and its Application to Resource Allocation and Sequencing Problems." In their treatment of "Two Machines in Series" (please refer to page 83 of [12]), they suggest that the jobs be partitioned into two classes: those which are to be on time and those which are to be late. The on-time jobs are sequenced according to Johnson's Rule:

$$\min\left\{a_j^{(1)}, a_{j+1}^{(2)}\right\} \leq \min\left\{a_{j+1}^{(1)}, a_j^{(2)}\right\}.$$

where: j = job

$a_j(1)$ = processing time of job j on machine 1

$a_j(2)$ = processing time of job j on machine 2

n = number of jobs

d = common deadline

The model then proceeds into a dynamic programming approach with the objective of minimizing the total loss by minimizing the total number of tardy jobs.

Their problem ([12], p. 83) is to partition the jobs into two classes, those which are to be on time and those which are to be late. The on-time jobs are sequenced by Johnson's Rule and are followed by the tardy jobs in arbitrary order. Then the dynamic programming approach is applied. In the problem being studied, the planning horizon and the jobs chosen are selected such that only one job at most will overlap into the next planning horizon. So, the use of dynamic programming is not required. Implementing Johnson's Rule only as the method of problem solution will result in the same sequence, and is the method selected for review. Johnson's problem, simply stated, is the two-machine flowshop problem with the objective of minimizing makespan. Johnson's rule is:

Job i precedes job j in an optimal sequence if

$$\min\left\{t_{i1}, t_{j2}\right\} \lesseqgtr \min\left\{\min t_{i2}, t_{j1}\right\} .$$

Makespan is defined as the length of time required to complete all jobs.

The algorithm for Johnson's Rule is given below:

Step 1. Find $\min_i \{t_{i1}, t_{i2}\}$

Step 2a. If the minimum processing time requires machine 1, place the associated job in the first available position in the sequence. Go to Step 3.

Step 2b. If the minimum processing time requires machine 2, place the associated job in the last available position in the sequence. Go to Step 3.

Step 3. Remove the assigned job from consideration and return to step 1 until all positions in the sequence are filled.

The variables' values based upon Appendices III and IV for this problem appear as shown below in Table VIII.

Table VIII

Data for Scheduling Problem

Section	Jobj	t_{j1}(hours)	t_{j2}(hours)
W18L	1	11.6	9.28
W12N-W12L	2	25.334	20.965
MC18	3	6.1	5.083
W16-W16L	4	47.967	41.14
PZ27	5	1.25	1.316
W10	6	9.917	9.135
W14	7	6.133	4.842

The time span of a week was chosen as the planning horizon not only for the manageability of the size of the problem, but also because the rolling schedule is actually projected on a weekly basis and is constantly updated. The derivation of the hours used for t_{j1} and t_{j2} is located in Appendix V.

The application of the algorithm can be followed in Figure V.

<u>Application of Johnson's Algorithm</u>

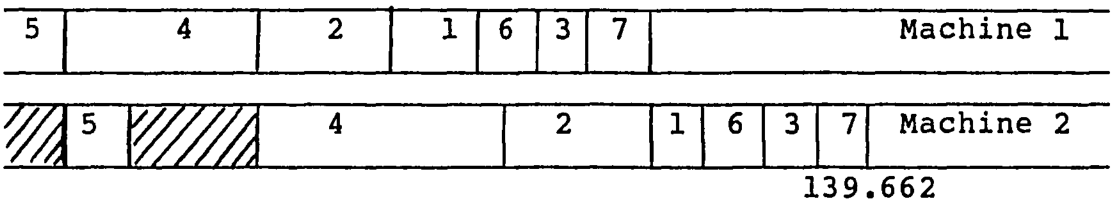
Stage	Unscheduled Jobs	min t_{ik}	Assignment	Partial Schedule
1	1,2,3,4, 5,6,7	t_{51}	5=(1)	5xxxxxx
2	1,2,3,4, 6,7	t_{72}	7=(7)	5xxxxx7
3	1,2,3,4,6	t_{32}	3=(6)	5xxxx3-7
4	1,2,4,6	t_{62}	6=(5)	5xxx6-3-7
5	1,2,4	t_{12}	1=(4)	5xx1-6-3-7
6	2,4	t_{22}	2=(3)	5x2-1-6-3-7
7	4	t_{42}	4=(2)	5-4-2-1-6-3-7

Figure V

The optimal solution is:

PZ27-W16-W16L-W12N-W12L-W18L-W10A-MC18-W14

The corresponding Gantt Chart is shown in Figure VI.



<u>Gantt Chart</u>

Figure VI

The Makespan is 139.662 hours, or 17.4578 eight-hour shifts. The number of shifts in a week in the study is 14 on the Blooming Mill and 18 on the Finishing Mill. Machine 1 is finished processing at 108.3010 hours, or 13.5376 eight-hour shifts. So, given this sequence, no job should extend into the succeeding week.

The inaccuracy in this model is that in actuality the jobs being processed on machine 1 do not have to reach completion before they begin their processing on machine 2. This situation is addressed using the algorithm presented in the next section.

<u>Choice and Application of Model</u>

In the case presented for analysis, a section can begin rolling on the Finishing Mill before it has finished rolling on the Blooming Mill. This is that ideal condition, which was described previously as "hot connect." This overlapping structure is called "lap-phasing" in the scheduling literature reviewed. The time that is required to roll enough bars of a given section on the Blooming Mill to fill one furnace with that section for the Finishing Mill will be designated as the earliest start time, a_j, or "start lag" for that section. In the same manner, the "stop lag" would also be the time, b_j, to empty one furnace for a given section. This is the rolling time for a section on the Finishing Mill for a specified furnace capacity.

The algorithm selected is an implementation of Johnson's Rule with start-lags and stop-lags. There is a specific interval, a_j, called a start lag, such that operation j2 can be started a_j time units after operation j1 begins. Lap-phasing allows $a_j < t_{j1}$, where t_{j1} is the processing time of job j on machine one and likewise t_{j2} is the processing time of job j on machine two. The interval b_j is a stop-lag such that operation j2 must not complete any earlier than b_j time units after operation j1 is completed.

The objective is to minimize makespan through optimal scheduling. The algorithm contains three steps:

Step 1: Let $U = \{j \mid t_{j1} < t_{j2}\}$ and $V = \{j \mid t_{j1} \geq t_{j2}\}$

Step 2: Define $y_j = \max\{a_j - t_{j1}, b_j - t_{j2}\}$

Arrange the members of set U in nondecreasing order to $t_{j1} + y_j$ and arrange the members of set V in nonincreasing order of $t_{j2} + y_j$.

Step 3: An optimal sequence is ordered set U followed by the ordered set V.

The furnace capacity dictates the values of a_j and b_j. Converting furnace capacity into hours is done by dividing the furnace capacity (that is, the number of blooms) by the rolling rate on the Blooming Mill as expressed in blooms per hour. Table IX, below, shows the values obtained. The values selected for t_{j1} and t_{j2} are the theoretical rolling times based on historical data. Please refer to Appendices I through V for further information.

Table IX

Data for Johnson's algorithm with Start-lags and Stop-lags

j	Section	t_{j1}	t_{j2}	a_j	b_j
1	PZ27	1.25	1.316	1.35	1.42
2	W16-W16L	47.967	41.14	1.48	1.05
3	W12N-W12L	25.334	20.965	1.56	1.29
4	W18L	11.60	9.28	1.35	1.08
5	W10A	9.917	9.135	1.73	1.60
6	MC18	6.10	5.083	1.40	1.17
7	W14	6.133	4.842	1.49	1.18

Application of the Algorithm:

Step 1: $U = \{j \mid t_{j1} < t_{j2}\} = \{1\}$

$V = \{j \mid t_{j1} \geq t_{j2}\} = \{2, 3, 4, 5, 6, 7\}$

Step 2: $y_j = \max \{a_j - t_{j1}, b_j - t_{j2}\}$

U: $y_1 = \max \{1.35 - 1.25, 1.42 - 1.316\} = 0.104$

V: $y_2 = \max \{1.48 - 47.967, 1.05 - 41.14\} = -40.09$

$y_3 = \max \{1.56 - 25.334, 1.29 - 20.965\} = -19.675$

$y_4 = \max \{1.35 - 11.6, 1.08 - 9.28\} = -8.20$

$y_5 = \max \{1.73 - 9.917, 1.6 - 9.135\} = -7.535$

$y_6 = \max \{1.40 - 6.10, 1.17 - 5.083\} = -3.913$

$y_7 = \max \{1.49 - 6.133, 1.18 - 4.842\} = -3.662$

U in nondecreasing order of $t_{j1} + y_j$: $\{1\}$

V in nonincreasing order of $t_{j2} + y_j$:

For V:

j	t_{j2}	+	y_j		
2	41.14	+	-40.09	=	1.05
3	20.965	+	-19.675	=	1.29
4	9.28	+	-8.20	=	1.08
5	9.135	+	-7.535	=	1.60
6	5.083	+	-3.913	=	1.17
7	4.842	+	-3.662	=	1.18

V = {5-3-7-6-4-2}

V = {W10A-W12N-W12L-W14-MC18-W18L-W16-W16L}

The previously determined sequences are quoted here for comparison:

General form of Johnson's Rule:

PZ27-W16-W16L-W12N-W12L-W18L-W10A-MC18-W14

Johnson's Rule with start-lags and stop-lags:

PZ27-W10A-W12N-W12L-W14-MC18-W18L-W16-W16L

Results

The algorithm that was chosen, the implementation of Johnson's Rule with start-lags and stop-lags, resulted in a sequence that did not mirror the results presented previously. The selection of a model to meet the idiosynchracies of an individual problem contributes significantly to the final solution.

Certain characteristics of the system demanded the use of the model selected.

1. Machine 2 could begin processing of a section before machine 1 was entirely finished. This required the time-lag consideration.
2. The objective of minimizing makespan was the most desirable performance measure because the on-time completion of all jobs for the week was the goal for jobs with a common deadline. Johnson's Rule addressed this issue.
3. Simplicity and speed of application was desired. The required computations for the algorithm selected are minimal in comparison to the branch-and-bound approach.

"With the start-lags or stop-lags in the model, it is not possible to guarantee that there exists an optimal schedule that is a permutation schedule. The results hold for permutation schedules; however, the best permutation schedule may not be an optimal solution."[1] Despite this lack of a guarantee for an optimal solution, it is still technically more important to start the jobs on machine 2 as soon as possible, thus forcing the use of a time-lag concept.

Markovian Decision Policy

The last factor to be addressed is the depleting of stock in the Bloom Yard. There are two sources of input to Stage 2. The blooms are either transferred directly from Stage 1 or they are taken from storage in the Bloom Yard. The high transfer and roller line that separate the stages decouple them. If Stage 2 is down, blooms are stocked in the Bloom Yard. If Stage 1 is down, blooms are taken from the Bloom Yard to keep Stage 2 active. But, this is not the only time that blooms are drawn from the Yard. Rolling directly from Stage 1 to Stage 2 and depleting the stock in the Yard is done simultaneously.

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[1]Kenneth R. Baker, Introduction to Sequencing and Scheduling, New York: John Wiley and Sons, 1974, p.148.

Because of the capacity of the high transfer and the roller line, there is invariably space available for drawing blooms from stock. Depleting stock then depends upon the condition of the high transfer and the roller line. The conditions will be referred to as states. There are two possible actions: take blooms from stock, K, or do not take blooms from stock, R.

The system has a countable number of states and a finite number of possible actions. The probability of the state of the system at t + 1 depends on neither t nor the history of the system prior to t. The process is stochastic in nature.

At this point, an optimal decision policy is developed for deciding whether or not the stock in the Yard is depleted for a given state. The stochastic nature of the process suggests a Markovian decision process. The policy, or rule for choosing an action at each point in time, is a stationary one because the action specified at time t depends upon only the present state. The use of a Markovian decision process determines the optimal policy. The procedure chosen is stated as a policy improvement algorithm, as shown in Howard [9]. The policy improvement algorithm is:

Step 1. For a stationary policy, f, solve the system of m + 1 equations given by

$$V_{f,\alpha}(i) = C[i, f(i)] + \alpha \sum_{j=0}^{m} P_{ij}[f(i)]\; V_{f,\alpha}(j) \quad (i = 0, 1, \ldots, m)$$

for the m + 1 unknown values of $V_{f,\alpha}(i)$.

Step 2. Find the stationary policy g such that for each state i, g(i) is the action that minimizes

$$C(i, a) + \alpha \sum_{j=0}^{m} P_{ij}(a)\; V_{f,\alpha}(j)$$

Use the values of $V_{f,\alpha}(i)$ from step 1.

Step 3. If $f(i) \neq g(i)$ for at least one i, then go to step 1 and use g in place of f. If f(i) = g(i) for all $i \in I_m$, then stop. Policy f is α-optimal.

The variables are defined as:

α is the discount factor where $0 < \alpha < 1$.

i is the state of the system

a is the action take at time t

$P_{ij}(a)$ is the probability that the system will be in state j at time t + 1

C(i,a) is the expected cost of action a in state i

$V_{f,\alpha}(i)$ is the optimal expected value function (the subscript α is not carried below on the values of $V_{f,\alpha}$ for convenience.)

At the beginning of each hour, the system is observed and classified into one of four possible states. After observing the state, a decision must be made whether or not to take blooms from stock.

The expected costs, C(i,a) for each i were based upon output per hour. Sixty is the base cost in blooms per hour. If the stock is being depleted, then the base cost is reduced by the number taken from stock in an hour when in state i. If the stock is not being depleted, then the cost is increased by the number that could have been taken from stock in an hour when in state i. If stock is being drawn from the Yard, then the output rate is enhanced by the additional blooms and the cost is lowered. The ability to draw blooms from the Yard is dependent upon the state, i, and is reflected in the cost for each i.

If blooms are taken from stock, k, then hourly operating costs of 60 - 40 = 20, 60 - 30 = 30, and 60 - 20 = 40 are incurred when in states 0, 1, and 2, respectively. If blooms are not taken, from stock, R, then the costs incurred are 60 + 30 = 90, 60 + 20 = 80, and 60 + 0 = 60 when in states 1, 2, and 3, respectively.

Possible actions:

R   do not take from stock

K   take from stock

Possible states:

0   roller line empty, high transfer empty

1   roller line empty, high transfer full

2   roller line half empty, high transfer full

3   roller line full, high transfer full

The data appears in Table X.

Table X

Data for Optimal Decision Policy for Stock Depletion

STATE i	ACTION a	COST $C(i,a)$	Probabilities $P_i(a)$	$P_{i1}(a)$	$P_{ij}(a)$ $P_{i2}(a)$	$P_{i3}(a)$
0	K	20	0	0	0.8	0.2
1	K	30	0	0	0.5	0.5
1	R	90	0.1	0.3	0.6	0
2	K	40	0	0.0	0.4	0.6
2	R	80	0.1	0.4	0.5	0.0
3	R	60	0	0	0.8	0.2

Suppose $\alpha = 0.90$.

Step 1. $f_1(0) = K,\ f_1(1) = K,\ f_1(2) = K,\ f_1(3) = R$

$$V_{f1}(0) = 20 + 0.9(0.8V_{f1}(2) + 0.2V_{f1}(3))$$

$$V_{f1}(1) = 30 + 0.9(0.5V_{f1}(2) + 0.5V_{f1}(3))$$

$$V_{f1}(2) = 40 + 0.9\ (0.4V_{f1}(2) + 0.6V_{f1}(3))$$

$$V_{f1}(3) = 60 + 0.9(0.8V_{f1}(2) + 0.2V_{f1}(3))$$

Solving the equations results in the following values:

$V_{f1}(0) = 817.14$ $\qquad$ $V_{f1}(1) = 817.50$

$V_{f1}(2) = 785.71$ $\qquad$ $V_{f1}(3) = 857.14$

Step 2. State 0: $C(0,a) + 0.9\sum_{j=0}^{3} P_{0j}(a)V_{f1}(j)$

Action = K. $(20 + 0.9(0.8(785.71) + 0.2(857.14)) = 740.0$

The same method is used for the rest of the states and actions.

States	Action	Value	Minimum
1	K	769.29	*
1	R	808.55	
2	K	785.71	*
2	R	801.41	
3	R	780.00	*

The policy in step 2:

$f_2(0) = K$, $f_2(1) = K$, $f_2(2) = K$, $f_2(3) = R$

This agrees with the policy of f_1.

Step 3. Stop. $f(i) = g(i)$. Policy f is α -optimal.

Results

The policy is to draw blooms from stock when the system is in states 0, 1, and 2 and not to draw when in state 3. The mill planners determine the probabilities and expected costs of the system.

CHAPTER IV

ENTIRE SYSTEM FLOW

Example of the Process

A plan for overall production control may now be presented. Chapter II developed a method of creating a curve that depicted the increase in output rate for every increase in buffer level given the prevailing operating characteristics. These characteristics are based upon historical information and will change as historical information is updated. The most current historical information is used, covering the desired span of time specified by the mills' planners.

Chapter III developed a method of pre-conditioning the weekly production for maximum efficiency by creating an optimal permutation schedule for the sections to be rolled in that week. The weekly rolling begins with a schedule that has the minimum makespan among the possible permutations. As delays in the rolling process occur, the graph is used to determine how much of each section should be stocked. If a stocking level is reached for a section and the delay on the Combination Mill is not finished, then the next succeeding section is stocked in the Bloom Yard. When the delay is over, the mill complex resumes its hot connect situation, which minimizes overall costs. In this manner, the minimum number of blooms is stocked to maintain a high production rate.

Since the minimum makespan is dependent upon achieving the greatest hourly system output, then the ideal buffer level is imperative because proper "storage capacity means less chance of blocking or starving and hence greater hourly system output."[1] The system output is monitored only at the end of the second stage. Because of this, only the times when stage two is down and stage one is working will be considered stocking time. If the two stages were not almost equivalent in their hourly output, this would not be true. If stage one would be substantially greater in its hourly output, then stocking would occur even as the mills were in a hot connect stance. If stage one were substantially lower in its hourly output, then stage one would have dedicated stocking shifts while stage two was down in order to maintain a steady flow of product at stage two when it is operating.

A review of the example presented throughout this paper may now be undertaken from the beginning of the developed procedure and followed to its end. The curve of production rate versus buffer level is developed from the gathered data. First, the data base is established, and then the Hewlett Packard hand-held calculator program is

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[1]Edward Ignall and Alvin Silver, "The Output of a Two-Stage System with Unreliable Machines and Limited Storage," AIIE Transactions, June 1977, Vol. 9, No. 2, p. 183.

used to develop the curve. In the example, the best stocking level appears to be 200 blooms. The corresponding value of R(z), or production rate, is 0.7910, which is 0.0005 less than the maximum R(z) possible for the given prevailing operating characteristics. Therefore, stocking above the 200-bloom level will not show any appreciable gain in the output rate. The small incremental reduction in cost would be demonstrated through the use of cost analysis by determining the marginal cost if cost information were available.

Having determined a buffer level limit, the planner now turns his attention to the schedule itself. The application of Johnson's Rule with start-lags and stop-lags reveals the optimal permutation schedule to minimize the total time for all sections to complete their processing. The schedule that was developed using Johnson's Rule with start-lags and stop-lags appears as:

PZ27-W10A-W12N-W12L-W14-MC18-W18L-W16-W16L

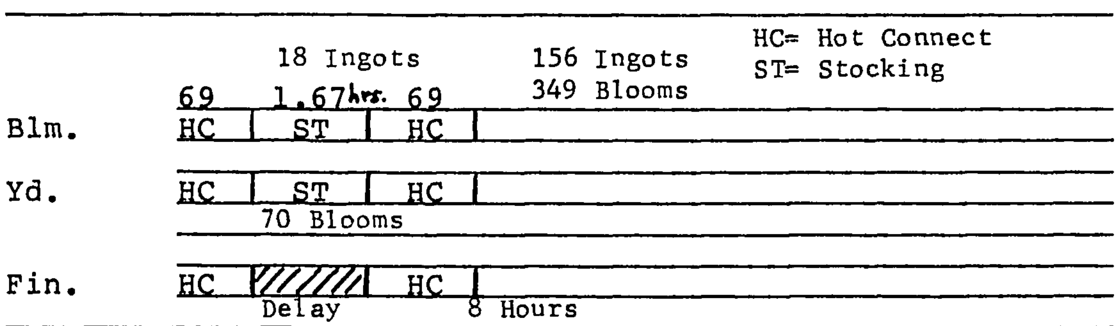
The actual rolling schedule did not look similar:

W18L-W12N-W12L-MC18-W16-W16L-PZ27-W16L-W10A-W14

In order to show how the curve would be utilized in conjunction with the rolling schedule, the schedule actually followed, with its recorded historical delays and other pertinent information, will be used. In practice, the optimal permutation would be used instead and the delays associated with it would determine the flow of material to either stock or hot connect.

The first operating shift of the week encountered delays on the Finishing Mill equaling 1.167 hours and no delays on the Blooming Mill. The maximum possible stocking hours would then be 1.167. The prevailing rate of the Blooming Mill was determined to be approximately 60 blooms per hour, as previously cited. The maximum possible number of blooms that were stocked on this shift was (1.167 hours)(60 blooms/hr) = 70.02, or approximately 70 blooms. The section being rolled on the shift was W18L and was succeeded by W12N. The 70 blooms would be W12N blooms and stocked in the Bloom Yard.

The corresponding Gantt Chart is shown in Figure VII.



Gantt Chart

Figure VII

The number of blooms that are left to be stocked if necessary is 200 - 70 = 130 blooms. The rolling for the week continues, using the timing of the delays and the 200-bloom buffer level as guides to decision-making.

Supporting information for the development of Figure V can be found in Appendices III and IV. The entire system flow and the decisions that would be made using the model presented are shown in Figure VIII.

From Figure VIII, it is shown that the model requires that an optimal permutation schedule be developed for the succeeding week as well. It is necessary to project the buffer stock for the upcoming sections. The buffer stock should be a few shifts ahead of the sections actually being rolled on the Finishing Mill to assure that the second stage has material to process.

In the turns that are processing W16L, the section is stocked several times to the 200-bloom level. The number of blooms ordered is substantial for this section, and each turn of its rolling is viewed as a separate section. This is because each turn uses the previously stocked 200 blooms. PZ27 is only stocked to 50 blooms because that was the size of the entire order.

The Markovian decision policy developed in Chapter III followed throughout the process to deplete the Yard. The policy was to draw blooms from stock when the system is in any condition other than state 3. State 3 was the condition that both the connecting roller line and high transfer were full.

The overall model is intended to serve as a guide-line, a management tool to be used as delays occur and decisions must be made for keeping the operations at a high level of output. The stocking levels and subsequent savings to be realized are highly dependent upon the delay hours experienced on both mills.

APPLICATION OF THE SYSTEM MODEL

Date	Shift	Fin. Delay Hours	Blm. Delay Hours	Stock- ing Hours	Equiv.# Stocked Blooms	Sec- tions	Ordered # Blooms	Stocking Details: #Blooms-Section
8-30	2	1.167	0.0	1.167	70.02	W18L	464	70-W12N
	3	2.667	0.917	1.750	105.00	W18-W12N		105-W12N
8-31	1	3.500	down	none	none	W12N	536	none
	2	3.083	0.667	2.416	144.96	W12N-W12L		145-W12L
	3	2.000	1.083	0.917	55.02	W12L	680	55-MC18
9-01	1	3.667	down	none	none	W12L-MC18	244	none
	2	3.333	0.667	2.666	159.96	MC18-W16		160-W16
	3	2.333	1.917	0.416	24.96	W16	420	25-W16L
9-02	1	2.250	down	none	none	W16-W16L	1682	none
	2	repair	0.833	7.167	430.02	repair		200-W16L;50-PZ27;180-W10A
	3	repair	1.667	6.333	379.98	repair		20-W10A;200-W14;160-W14L
9-03	1	4.583	down	none	none	W16L-PZ27		none
	2	7.083	1.333	5.750	345.00	PZ27	50	200-W16L;40-W14L;105-W16L
	3	2.750	repair	none	none	PZ27-W16L		none
9-04	1	1.500	1.167	0.333	19.98	W16L		20-W16L
	2	2.750	3.000	none	none	W16L		none
	3	2.667	2.167	0.500	30.00	W16L		30-W16L
9-05	1	3.417	down	none	none	W16L-W10A		none
	2	1.083	0.667	0.416	24.96	W10A	475	25-8x8
	3	3.167	1.333	1.834	110.04	W14	276	110-8x8
Total					1800.00		4827	Stock level = 37.29%

Figure VIII

CHAPTER V

CONCLUSIONS

The purpose of this study was to develop a decision-making tool that would indicate how to efficiently utilize an intermediate storage area with respect to an efficient production schedule. The tool took the form of utilizing a heuristic procedure presented by Ignall and Silver to determine stocking levels that could improve production output. The implementation of Johnson's Rule with start-lags and stop-lags generated an efficient permutation schedule as a framework for rolling and stocking. The objective of the scheduling algorithm was to minimize makespan. Blooms were taken from stock by adherence to a Markovian decision policy.

The original concept of the ideal situation was the "hot connect" condition in which no delays are incurred and the flow of blooms is continuous from stage one to stage two. In actual practice, the stocking of blooms leads to a higher output rate because it addresses the issue of delays. The question then becomes that of how much stocking is to be done to achieve the ideal situation of continuous material flow.

Figure IV demonstrates the production output for a buffer level of zero versus an infinite buffer level. Under the prevailing characteristics in the example, an increase of approximately 9.41% in output can be enjoyed by supplying an infinite buffer. This equated to an additional 45 bars per shift. But an infinite buffer need not be supplied because the same output level is achieved at a range of a 200- to 300-bloom level. Stocking above this level will not increase the output rate. So, the model becomes valuable in determining the most efficient stocking level limit.

According to the graph, operations in sequence that differ to a great extent in failure hours, repair hours, and rolling rates experience a smaller stocking level to reach the maximum output rate. Operations with more uniform characteristics rise to the maximum output rate at a much slower pace. The equation for R(z) itself is an interpolation model;

$$R(z) = R_O + (R_\infty - R_O)\, m(z),$$

in which R_∞ and R_O serve as the limits and z determines the values within those limits. Ignall and Silver based their results on simulations; actual data was used to determine the curve in Figure IV.

The scheduling model formed the base upon which the buffer level decisions were applied. The optimal permutation schedule is developed to minimize the time needed to process all of the jobs. The implementation of Johnson's Rule with start-lags and stop-lags took into consideration the fact that sections may begin rolling on the Finishing Mill prior to their completion on the Blooming Mill. Although there is no guarantee that the schedule is optimal, the model is still technically more appropriate for the problem than is current practice and will be near-optimal. The Markovian decision policy formed the basis upon which the stock was depleted. The policy depends upon the costs and probabilities as determined by the mill planners.

By utilizing the schedule, the buffer level, and the stock depletion policy, the goal of increasing the production rate is approached using three independent heuristic algorithms. The potential time savings will be noticed in an increase in the output per hour, in the reduction of delays, and in the reduction in the volume of material handling activities.

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APPENDIX I BLOOMING MILL HISTORICAL DATA BASE

Date	Shift	# Ingots	Total Turn Hours	Total Delay Hours	Total Oper. Hours	Failure Hours	Repair Hours	Roll Chg + Sect. Hours
8-21	1	63	8	0.833	7.167	0.75	0.083	0.0
	2	108	8	1.750	6.250	1.167	0.5833	0.0
	3	115	4.5	1.083	3.417	0.417	0.6670	0.0
8-22	2	91	8	2.167	5.833	1.167	1.000	0.0
	3	111	8	1.917	6.083	0.250	1.667	0.0
8-23	2	89	8	3.500	4.500	0.0	3.500	0.0
	3	118	6	0.0	6.000	0.0	0.0	0.0
8-24	2	125	8	1.167	6.833	1.083	0.083	0.0
	3	105	8	1.333	6.667	1.250	0.083	0.0
8-25	2	129	8	0.0	8	0.0	0.0	0.0
	3	121	8	0.75	7.25	0.167	0.583	0.0
8-26	2	133	8	0.333	7.667	0.333	0.0	0.0
	3	120	8	1.583	6.417	0.0	1.583	0.0
8-28	1	116	8	1.167	6.833	0.500	0.667	0.0
	2	138	8	1.083	6.917	1.083	0.0	0.0
	3	136	8	1.417	6.583	1.417	0.0	0.0
8-29	2	121	8	1.00	7.00	1.00	0.0	0.0
	3	137	8	0.583	7.417	0.583	0.0	0.0
8-30	2	156	8	0.0	8	0.0	0.0	0.0
	3	112	8	0.917	7.083	0.167	0.750	0.0

APPENDIX I BLOOMING MILL HISTORICAL DATA BASE

Date	Shift	# Ingots	Total Turn Hours	Total Delay Hours	Total Oper. Hours	Failure Hours	Repair Hours	Roll Chg + Sect. Hours
8-31	2	122	8	0.667	7.333	0.167	0.500	0.0
	3	109	8	1.083	6.917	0.417	0.667	0.0
9-01	2	135	8	0.667	7.333	0.0	0.677	0.0
	3	102	8	1.917	6.083	0.417	1.500	0.0
9-02	2	117	8	0.833	7.167	0.583	0.250	0.0
	3	112	8	1.667	6.333	1.417	0.250	0.0
9-03	2	117	8	1.333	6.667	0.917	0.0	0.417
9-04	1	119	8	1.167	6.833	0.333	0.833	0.0
	2	89	8	3.000	5.000	3.000	0.00	0.0
	3	91	8	2.167	5.833	0.667	1.50	0.0
9-05	2	123	8	0.667	7.333	0.167	0.50	0.0
	3	122	8	1.333	6.667	1.333	0.0	0.0
9-06	2	128	8	0.333	7.667	0.333	0.0	0.0
	3	134	8	0.167	7.833	0.167	0.0	0.0
9-07	2	144	8	0.667	7.333	0.333	0.333	0.0
	3	134	8	0.500	7.500	0.500	0.0	0.0
9-08	2	113	8	1.417	6.583	0.167	1.25	0.0
	3	112	8	0.500	7.500	0.333	0.167	0.0
9-09	2	114	7	0.833	6.167	0.0	0.833	0.0
	3	130	6	0.250	5.750	0.250	0.0	0.0

APPENDIX I BLOOMING MILL HISTORICAL DATA BASE

Date	Shift	# Ingots	Total Turn Hours	Total Delay Hours	Total Oper. Hours	Failure Hours	Repair Hours	Roll Chg + Sect. Hours
9-10	2	114	8	1.667	6.333	0.333	1.333	0.0
9-11	1	97	8	2.50	5.50	0.0	2.50	0.0
	2	74	6.3	2.167	4.133	2.167	0.0	0.0
	3	114	8	0.667	7.333	0.167	0.50	0.0
9-12	2	120	8	1.500	6.500	0.833	0.667	0.0
	3	139	8	0.417	7.583	0.0	0.417	0.0
9-13	2	171	8	0.0	8.0	0.0	0.0	0.0
	3	130	8	0.667	7.333	0.667	0.0	0.0
9-15	2	133	8	0.583	7.417	0.417	0.167	0.0
	3	130	8	0.167	7.833	0.167	0.0	0.0
9-16	2	120	8	0.667	7.333	0.250	0.417	0.0
	3	118	8	0.500	7.500	0.0	0.500	0.0
9-17	2	130	8	0.750	7.250	0.50	0.250	0.0
9-18	1	164	8	0.0	8.0	0.0	0.0	0.0
	2	131	8	0.833	7.167	0.417	0.417	0.0
	3	154	8	0.167	7.833	0.0	0.167	0.0
9-19	2	121	8	1.167	6.833	1.167	0.0	0.0
	3	134	8	2.333	5.667	0.0	2.333	0.0
9-22	2	119	8	1.583	6.417	1.583	0.0	0.0
	3	135	8	1.083	6.917	1.083	0.0	0.0

APPENDIX II FINISHING MILL HISTORICAL DATA BASE

Date	Shift	Section	# Blooms	Total Turn Hours	Total Delay Hours	Total Oper. Hours	Failure Hours	Repair Hours	Roll Chg + Sect. Hours
8-21	1	W81-8x4	349	6.3	2.333	3.967	0.75	0.0	1.583
	2	8x4	383	8	3.167	4.833	2.417	0.0	0.750
	3	8x4-W6	389	8	2.417	5.583	0.917	0.0	1.500
8-22	1	W6-W6L	433	8	2.750	5.250	1.500	0.167	1.083
	2	W6L-5x4 1/2BA	305	8	3.500	4.500	1.830	0.083	1.583
	3	5x4 1/2BA	157	7	4.250	2.750	4.250	0.0	0.000
8-23	1	Down							
	2	Down							
	3	5x4 1/2BA	176	8	5.167	2.833	2.500	1.417	1.250
8-24	1	W4	276	8	3.417	4.583	3.333	0.0	0.083
	2	W4-MC8A	418	8	2.417	5.583	0.833	0.250	1.333
	3	MC8A-MC8	428	8	1.500	6.500	0.250	0.167	1.083
8-25	1	MC8-W10N	410	8	1.833	6.167	1.250	0.0	0.583
	2	W10N	276	8	3.417	4.583	2.750	0.0	0.667
	3	W10N-6x4	384	8	2.667	5.333	1.333	0.0	1.333
8-26	1	6x4-W10L	585	8	3.167	4.833	1.0833	0.167	1.917
	2	Repair							
	3	W10L-C7	474	8	2.333	5.667	0.9170	0.0	1.417
8-28	1	Cancelled							
	2	C12	382	8	1.917	6.083	0.917	0.0	1.000
	3	C12-S8	248	8	2.167	5.833	0.417	0.167	1.583

APPENDIX II FINISHING MILL HISTORICAL DATA BASE

Date	Shift	Section	# Blooms	Total Turn Hours	Total Delay Hours	Total Oper. Hours	Failure Hours	Repair Hours	Roll Chg + Sect. Hours
8-29	1	S8	408	8	1.833	6.167	1.833	0.0	0.0
	2	S8-W18-18L	181	8	4.000	4.000	1.667	0.0	2.167
	3	W18L	300	8	2.167	5.833	1.417	0.0	0.750
8-30	1	Down							
	2	W18L	349	8	1.167	6.833	1.167	0.0	1.333
	3	W18L-W12N	230	6.7	2.667	4.033	1.000	0.5	1.333
8-31	1	W12N	266	8	3.500	4.500	0.927	2.5	0.083
	2	W12N-W12L	310	8	3.083	4.917	1.833	0.417	0.833
	3	W12L	396	8	2.000	6.000	1.917	0.0	0.083
9-01	1	W12L-MC18	256	8	3.667	4.333	1.000	1.000	1.667
	2	MC18-W16	233	8	3.333	4.667	1.333	0.0	2.000
	3	W16	178	5.5	2.333	3.167	0.0	2.25	0.083
9-02	1	W16-W16L	257	7.5	2.250	5.250	0.417	0.75	1.083
	2	Repair							
	3	Repair							
9-03	1	W16-PZ27	185	8	4.583	3.417	1.667	1.917	1.000
	2	PZ27	39	8	7.083	0.917	0.417	0.167	6.500
	3	PZ27-W16L	206	8	2.750	5.250	1.083	0.0	1.667
9-04	1	W16L	388	8	1.50	6.500	1.50	0.0	0.0
	2	W16L	314	8	2.75	5.25	2.75	0.0	0.0
	3	W16L	352	8	2.667	5.333	2.667	0.0	0.0

APPENDIX II FINISHING MILL HISTORICAL DATA BASE

Date	Shift	Section	# Blooms	Total Turn Hours	Total Delay Hours	Total Oper. Hours	Failure Hours	Repair Hours	Roll Chg + Sect. Hours
9-05	1	W16L-W10A	234	8	3.417	4.583	1.667	0.0	1.750
	2	W10A	358	8	1.083	6.917	1.083	0.0	0.0
	3	W14	276	8	3.167	4.833	2.083	0.0	1.083
9-06									
	1	Down							
	2	W14-W14L	355	8	2.50	5.50	1.50	0.0	1.00
	3	W14L	297	8	3.333	4.667	2.917	0.0	0.417
9-07	1	W14L	347	8	2.667	5.333	2.583	0.0	0.083
	2	W14L-8x8	230	8	3.250	4.750	2.083	0.0	1.167
	3	8x8	386	8	1.333	6.667	1.250	0.083	0.0
9-08	1	8x8-W10N	344	8	2.833	5.167	1.083	0.250	1.50
	2	W10N-W10L	429	8	1.833	6.167	0.50	0.0	1.333
	3	W10L-C10	421	8	1.917	6.083	0.50	0.0	1.417
9-09	1	C10	446	7	0.917	6.083	0.583	0.250	0.083
	2	Repair							
	3	Repair							
9-10	1	W12A-C10	244	8	3.833	4.167	0.917	0.0	2.917
	2	MC12-W18	215	7.4	2.583	4.817	0.417	0.417	1.750
	3	Cancelled							

APPENDIX II FINISHING MILL HISTORICAL DATA BASE

Date	Shift	Section	# Blooms	Total Turn Hours	Total Delay Hours	Total Oper. Hours	Failure Hours	Repair Hours	Roll Chg + Sect. Hours
9-11	1	W18L	368	8	1.583	6.417	1.50	0.0	0.083
	2	W18L	289	8	2.167	5.833	1.50	0.667	0.0
	3	W18L	307	8	1.250	6.750	1.083	0.0	0.0
9-12	1	W18L-C8	243	8	0.0	8.0	0.0	0.0	0.0
	2	C8	490	8	1.05	6.95	0.667	0.083	0.333
	3	C8	469	8	1.00	7.00	1.00	0.0	0.0
9-13	1	C8-S7	64	5	3.833	1.167	2.333	0.0	1.500
	2	S7-W6	370	8	2.917	5.083	0.333	0.917	1.667
	3	W6	490	8	1.250	6.750	1.250	0.0	0.0
9-15	1	7x4-W8	354	8	3.167	4.833	2.333	0.0	0.833
	2	W8	325	8	3.500	4.500	1.000	1.50	1.0
	3	W8-W8L	506	8	1.250	6.750	0.167	0.0	1.083
9-16	1	W8L	470	8	1.50	6.50	0.667	0.833	0.0
	2	Repair							
	3	W8L-MC6B	307	8	3.667	4.333	1.917	0.250	1.5
9-17	1	MC6B	541	8	0.667	7.333	0.250	0.417	0.0
	2	MC6B-PZ27	283	8	3.167	4.833	1.333	0.0	1.833
	3	PZ27	178	8	3.50	4.500	3.500	0.0	0.0
9-18	1	PZ27	137	8	3.667	4.333	3.667	0.0	0.0
	2	PZ27-W8B	95	8	5.250	2.750	2.667	0.0	2.583
	3	W8B	261	8	3.750	4.250	2.333	0.0	1.417

APPENDIX II FINISHING MILL HISTORICAL DATA BASE

Date	Shift	Section	# Blooms	Total Turn Hours	Total Delay Hours	Total Oper. Hours	Failure Hours	Repair Hours	Roll Chg + Sect. Hours
9-19	1	W8B	280	8	3.083	4.917	2.167	0.917	0.0
	2	W8B-HP8	355	8	0.833	7.167	0.583	0.250	0.0
	3	W8B-W8A	309	8	3.417	4.583	2.000	0.0	1.417
9-22	1	MC6A	475	8	1.250	6.750	0.250	0.0	1.00
	2	MC6A-MC6	354	8	2.083	5.917	0.333	0.0	1.75
	3	W10A-W16	347	8	1.750	6.250	0.750	0.0	1.00

APPENDIX III

SCHEDULING EXAMPLE - DATA BASE

BLOOMING MILL

Date	Shift	# Ingots	Turn Hours	Delay Hours	Operating Hours
8-30	2	156	8	0	8
	3	112	8	0.917	7.167
8-31	2	122	8	0.667	7.333
	3	109	8	1.083	6.917
9-01	2	135	8	0.667	7.333
	3	102	8	1.917	6.083
9-02	2	117	8	0.833	7.167
	3	112	8	1.667	6.333
9-03	2	117	8	1.333	6.667
	3	repair			
9-04	1	119	8	1.167	6.833
	2	89	8	3.000	5.000
	3	91	8	2.167	5.833
9-05	2	123	8	0.667	7.333
	3	122	8	1.333	6.667
TOTAL		1626	112	17.418	94.663

APPENDIX IV

SCHEDULING EXAMPLE - DATA BASE

FINISHING MILL

Date	Shift	Section	# Blooms	Turn Hours	Delay hours	Operating Hours
8-30	2	W18L	349	8	1.167	6.833
	3	W18-12N	230	6.7	2.667	4.033
8-31	1	W12N	266	8	3.500	4.500
	2	W12N-W12L	310	8	3.083	4.917
	3	W12L	396	8	2.000	6.000
9-01	1	W12L-MC18	256	8	3.667	4.333
	2	MC18-W16	233	8	3.333	4.667
	3	W16	178	5.5	2.333	3.167
9-02	1	W16-W16L	257	7.5	2.250	5.250
	2	repair				
	3	repair				
9-03	1	W16L-PZ27	185	8	4.583	3.417
	2	PZ27	39	8	7.083	0.917
	3	PZ27-W16L	206	8	2.750	5.250
9-04	1	W16L	388	8	1.500	6.500
	2	W16L	314	8	2.750	5.250
	3	W16L	352	8	2.667	5.333
9-05	1	W16L-W10A	234	8	3.417	4.583
	2	W10A	358	8	1.083	6.917
	3	W14	276	8	3.167	4.833
TOTAL			4827	139.70	53.000	86.700

APPENDIX V

DERIVATION OF HOURS

Section	# Ingots	# Cuts/ Ingot	# Blooms	Theo. Rate min/ ingot	Theo. TTR hrs t_{j1}	Act. Rate min/ ingot	Act. TTR hrs
Blooming Mill							
W18L	232	2		3	11.60	3.3267	12.8634
W12N	134	4		5	11.167	5.203	11.620
W12L	170	4		5	14.167	3.140	8.900
MC18	122	2		3	6.100	2.9016	5.900
W16	210	2		3	10.500	3.0800	10.780
W16L	562	3		4	37.467	3.6650	35.320
PZ27	25	2		3	1.250	3.5040	1.460
W10A	119	4		5	9.917	5.042	10.000
W14	92	3		4	6.133	4.348	6.667
Finishing Mill							
				blooms/ hour	t_{j2}	blooms/ hour	
W18L			464	50	9.28	52.4	8.8495
W12N			536	58	9.241	59.72	8.9750
W12L			680	58	11.724	64.00	10.6250
MC18			244	48	5.083	54.2	4.5000
W16			420	56	7.500	51.69	8.1255
W16L			1682	50	33.640	56.07	30.0000
PZ27			50	38	1.316	31.57	1.5840
W10A			475	52	9.135	51.58	9.2085
W14			276	57	4.842	57.11	4.8330

VITA

PERSONAL HISTORY:

Name:	Deborah Louise Halkins
Birth Place:	Bethlehem, Pennsylvania
Birth Date:	July 13, 1957

INSTITUTIONS ATTENDED:

Freedom High School

Bethlehem, Pennsylvania	Graduated 1975

The Pennsylvania State University

B. S. I. E	Graduated 1979

Lehigh University

Candidate for M.S.I.E.	1983

HONORS:

Dean's List, The Pennsylvania State University

PROFESSIONAL EXPERIENCE:

Looper (Management Trainee), Technical Assistant, Engineer:

Bethlehem Steel Corporation

Industrial Engineer:

Brookhaven National Laboratory

PROFESSIONAL ORGANIZATIONS:

Senior Member, American Institute of Industrial Engineering

Parents: James and Grace Halkins