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Title: ANALYSIS OF SINGLE-CHANNEL MAINTENANCE COSTS

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This thesis is a study of certain costs relevant to the repair of process line equipment. A specific production configuration is studied through computer simulation and statistics. The significance of the simulated costs are investigated and related to practical production problems.

Costs relevant to the "permanent repair" of production equipment on the single-channel of an n-one-n production configuration are examined. A piece of equipment is assumed to be "permanently repaired" if it is modified or replaced, thus halting the breakdowns previously plaguing the machine. An n-one-n production configuration is a group of process lines (multi-channel), each manufacturing the same product, supplying a single process line (single-channel) with raw materials which in turn are used to supply dependent multi-channel process lines downstream with raw materials.

Costs deemed important to the permanent repair of single-channel production equipment are:

1. the cost of breakdown repair,
2. the cost of single-channel idle time,
3. the cost of downstream multi-channel idle time due to single-channel breakdowns, and
4. the cost of additional in-process inventory required to prevent the costs of (2) and (3).

Computer simulation is used to analyze the impact of single-channel breakdowns. The computer model simulates levels of single-channel idle time, ranging from 50% to 15% to reveal the effects of single-channel disrepair on the downstream multi-channel.

The application of the study is based on data from an aluminum fabrication plant. The upstream multi-channel is where ingots are cast out of molten aluminum, the single-channel is where these ingots are rolled into coils, and the downstream multi-channel is where the coils are fabricated into forms desired by customers, such as corrugated metal or small widths of metal.

Two key costs are found to be most important to the permanent repair decision: (1) the cost of single-channel idle time due to breakdowns, and (2) the cost of repairing a breakdown each time it occurs. These two costs comprise 84% of all expense resulting from breakdowns.

In-process inventory is also very important to the operation of the plant. Without it, downstream idle time would occur and millions of dollars of sales would be lost due to order cancellations from delivery delays.

Since every production system will have unique costs and individual characteristics, the actual cost findings of this study are not universally applicable. However, the methods used in deriving these costs are applicable to other plants having an n-one-n production configuration. The observations and techniques presented are a step towards improved decision making in maintenance, a topic which merits attention but has been partially ignored to date.

Analysis of Single-Channel Maintenance Costs

by

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ANALYSIS OF SINGLE-CHANNEL MAINTENANCE COSTS

I. INTRODUCTION

Maintenance is an important item of cost in many business firms. Proper maintenance can mean the difference between red and black entries in the annual Profit and Loss statement; the old adage:

For want of a nail a shoe was lost
For want of a shoe a horse was lost
For want of a horse a rider was lost
For want of a rider a message was lost
For want of a message a kingdom was lost
And all for the want of a horse-shoe nail!

is as true today as when it was first penned.

Expenditures for the repair of equipment breakdowns often consume a significant portion of the maintenance budget. A question often facing a plant manager is: Should a piece of equipment which has been breaking down frequently be temporarily[1] or permanently repaired[2]? The question is typically answered by a comparison of the cost of temporary repair versus the cost of permanent repair.[3]

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[1]Temporary repair is the "stopgap" repair of a machine that has suffered a breakdown. It is done in the expectation that the breakdown will probably occur again in the near future. Temporary repair is performed to get the machine going again as soon as possible so as not to interrupt production.

[2]Permanent repair is a "curative" repair, modification or replacement of a piece of equipment. It involves a large expenditure made in expectation of completely eliminating the breakdown currently idling the piece of equipment. This definition is referred to as permanent repair or major maintenance.

[3]This comparison is commonly called the "major maintenance decision" at the facility studied.

While such a comparison usually results in a lower maintenance budget it does not assure the firm's optimal spending level. To arrive at an optimal level of plant spending, costs other than those of repair must be considered. These other costs are dependent upon the configuration of the production machinery within the plant.

Machines can be placed in series[4] or parallel[5], with or without in-process inventory between each one. Any manufacturing facility is basically just a combination of these two simple configurations. The dependence of costs, other than those of repair, upon the machine configuration is illustrated by an example.

Consider a machine linked in series with several other machines, all without inventory between them. A breakdown of the machine in question will halt the flow of raw materials from it to the machines down the line. These downstream machines will therefore suffer delays since they will have nothing to work with. Since each of these delays is caused by the breakdown, the temporary versus permanent repair decision must consider all the delay costs, not just those occurring on the machine which suffered the breakdown.

As a contrast, consider a group of machines arranged in parallel, again with no in-process inventory between each machine. If

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[4]Machines of different function placed one after the other. This definition is referred to as series, single-channel or line.

[5]Machines or processes of identical function producing the same product. This definition is referred to as parallel or multi-channel.

each line is producing the same product, a breakdown of one of the machines in one of the lines will not interrupt the output of the other channels because the other channels are not dependent upon the broken line for raw material. In a multi-channel configuration only the delay costs of the broken channel are relevant to the temporary versus permanent repair decision.

Since the temporary versus permanent repair decision is dependent upon machine configuration, this study concentrates on one configuration, that of a parallel, series, parallel[6] production system. This configuration is shown in Figure 1. The breakdowns occurring on the single channel, and their affect, are examined.

Several costs are hypothesized as correlated to breakdowns of the single channel. These costs are:

1. the cost of downtime on the single channel,
2. the cost of downtime on the downstream parallel channel which occurs as a result of a single-channel breakdown,
3. the cost of sales which are lost due to the single-channel breakdowns, and
4. the cost of additional in-process inventory which must be stored to prevent the costs of (2) and (3) from occurring.

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[6]To be referred to as an n-one-n configuration.

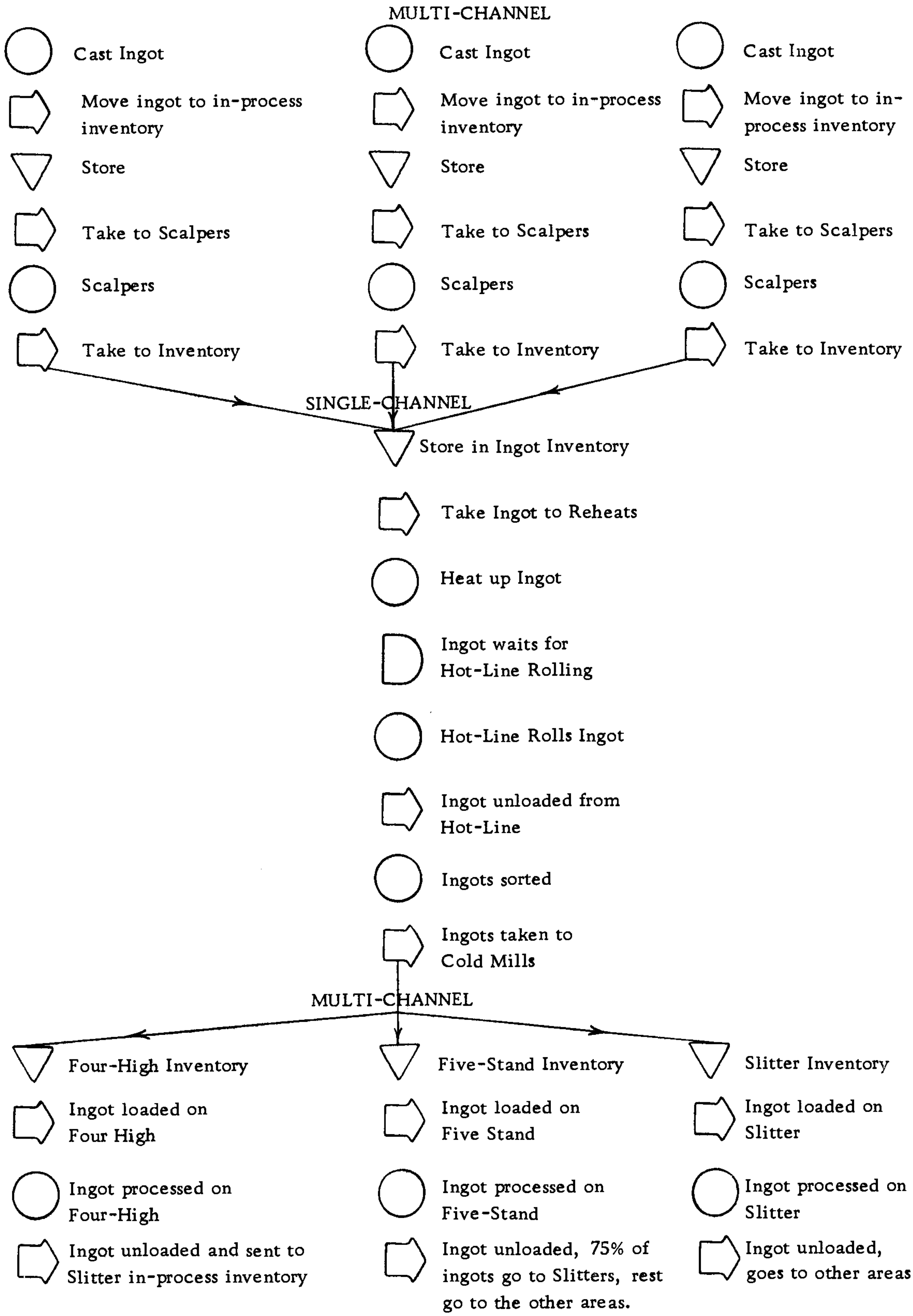


Figure 1. Production configuration studied.

Using these costs as inputs to temporary versus permanent repair decisions should assure a more optimal repair policy than was previously attainable.

The maintenance operation with which this treatise deals is owned and operated by Kaiser Aluminum and Chemical Corporation in Spokane, Washington. The facilities at Kaiser are used as an example but the observations are universal. Utilizing the Kaiser data, this thesis is addressed to three primary objectives.

1. Examination and quantification of the costs resulting from single-channel breakdowns in an n-one-n production configuration. This examination is made through the use of simulation and statistics in Chapters IV and V.
2. Determination of the relative importance of each of the costs studied. This determination is made by analysis of the fractional portion of the total cost contributed by each cost category and is performed in Chapter VI.
3. Organization of all costs into a useful, properly indexed format as a management decision making tool. This routine is developed currently with (1) and (2) above and is given in Appendix A.

All organizations cannot use the same cost categories to determine the optimal level of major maintenance at their production facilities. Operating costs vary from industry to industry and another organization would have to assemble its own data base. This study demonstrates how to use such a data base for a different company with an n-one-n production configuration and arrive at the optimal single-channel repair level.

The techniques used in this work are presented to facilitate other studies of an n-one-n configuration. An investigation of the hourly operating costs of the single channel is needed to determine the cost of downtime at the single channel. This hourly rate is then multiplied by the number of hours per year consumed by single-channel breakdowns to derive the annual cost of single-channel downtime.

Single-channel cost of lost sales is determined by ascertaining the probability that single-channel breakdowns will occur frequently enough within a given period of time to precipitate a lost sale. The probability is found through statistical analysis.

Cost of downtime at the downstream parallel channel is found in this work through computer simulation. The affect of various production levels which correspond to various degrees of single-channel disrepair are observed in a series of simulations. The cost of additional in-process inventory is also found by simulation.

Parallel channel lost sales are determined through the use of statistical techniques.

II. LITERATURE SEARCH

Since the major maintenance decision is based on cost information, a literature search was conducted in hope of finding appropriate cost data. Unfortunately, data of this sort is largely proprietary and has apparently not been published. This is the reason works such as "United States Air Force Radar Efficiency Tables" are not currently available.

The lack of relevant cost studies limited the literature search in two areas: (1) an examination of information gathering systems, and (2) statistical distributions which commonly occur in the area of maintenance.

Information Gathering Systems for Maintenance

The information gathering system used by the maintenance department at Kaiser Aluminum typifies limited data collecting abilities; it is basically a manual record keeping technique. The manual technique at Kaiser forced this study to use some estimates of data since the real data were not available. Accuracy is lost when estimates are used in lieu of real numbers. The loss of accuracy could very well invalidate many of the findings of this study. It is worthwhile, therefore, to examine more accurate data retrieval systems used in maintenance applications. If the results of this study appear encouraging, perhaps installation of such a system deserves consideration. If not, then no money need be spent for accuracy which is not needed.

Computerized Data Retrieval Systems for Maintenance

A 1966 Industrial Engineering Journal article (8) suggests a list of possible data relevant to a maintenance department in a manufacturing facility:

1. The idle time of machinery waiting for a maintenance crew.
2. Idle time of maintenance personnel.
3. Time required for a maintenance job.
4. A detailed description of work done on any job.
5. The parts required for repair.
6. The labor hours, by craft, required for each activity.
7. Costs incurred because the productive unit is down.
8. The reason for the productive unit being idle. (8, p. 468)

While these records are highly desirable, they are also difficult to obtain. There are very few "standard" jobs in maintenance, since anything which breaks down with sufficient frequency for it to become well-known to the maintenance manager is usually permanently repaired or replaced.

The enormity of the task of manually keeping the type of records suggested above can be greatly eased by the use of a computer. In "The Complete Computerized Maintenance System" by Turban (9), a complex computer control system is suggested. This system performs the tasks of record keeping (in its master files), preventive maintenance scheduling, and regular maintenance control. As Turban asserts:

> The routine task of keeping a history of all individual equipment, noting their costs, all repairs and modifications and their costs, can involve huge amounts of paperwork. This is probably the major reason why most companies do not have this valuable information. But a computer can maintain up-to-date records of all major repairs, parts replacement, and breakdown diagnosis. The information is recorded directly from field reports and returned work orders.
>
> Another file can be kept for all preventive maintenance instructions and frequencies. Also, time standards for executing the instructions as well as the material required can be listed here. (9, p. 22)

While this system sounds quite nice, Turban gives no details about implementation or savings.

The savings which may result from keeping good records of the maintenance operation are very important. These savings were considered when a computerized maintenance record-keeping system was installed at Texas Instruments Corporation (1):

> The costs of equipment, programming, system analysis and daily operations must be weighed against the ability to make decisions from the readout obtained. That is, offset costs by making money-saving decisions you could not make without the computer. You should compare the costs of providing a determined level of input data accuracy with the accuracy requirements for the output data. A strong belief in the need for the control mechanism and confidence in the results it might produce must be developed. Any controls applied to an organizational function must be aimed at reaching the company's objective. (1, vol. 16, p. 24)

Implementing a data retrieval system can be costly and time consuming; Texas Instruments spent two man years developing theirs, but the experience at Texas Instruments is a good example of the possibilities inherent in a computerized system.

Texas Instruments Corporation (1) used their computerized maintenance record-keeping system for compiling:

1. Accounting Costs. This report was a tracking device for all monies expended on all plant engineering activities by the maintenance organization.
2. Scheduling. TI used the computer for scheduling all the programmed maintenance of production and facilities equipment. In the overall maintenance planning and scheduling system, a report was published showing actual vs. estimated costs for open and closed end jobs.
3. Historical Records. A natural by-product of the scheduling program was the development of history records for individual pieces of equipment. Economic evaluation of a history record system often indicates that a semi-manual system is required. (This is due to excess coding required in the computer for recording each individual, but infrequent, breakdown).
4. Material Usage. The total program covered: (a) usage, (b) reorder points, (c) standard costs, (d) inventory turns, (e) job material costs, (f) material costs by mechanic, (g) cataloging, (h) inventory levels and e. o. q. (1, vol. 16, p. 23)

It is interesting to note that a company has been able to install a semi-computerized record-keeping system. The comment in #3 of the quote is an eye-opener, indicating that not using the computer in some cases is a wise policy. The experiences at Texas Instruments are used to illustrate that it is possible to build a more accurate data base than the one used in this thesis.

Most of the data concerning the frequency and duration of breakdowns in this thesis is derived from estimates by maintenance personnel. While these estimates are felt to be fairly accurate, they do not approach the accuracy that would be available if a computerized data retrieval system were used at Kaiser.

The rest of the data is quite accurate because the Planning Department of Kaiser Aluminum makes full use of a computer in determining production rates and things of this nature. It is only in the area of maintenance, specifically the history of breakdowns, in which data are less than perfect.

As an aside, Texas Instruments found one usage of its computerized system which they had not foreseen. The materials usage portion of the computer application proved very beneficial for Texas Instruments as indicated by the following testimonial:

> A feature of the EDP materials program that aided management immensely was a contract tie-in with one of the suppliers. This supplier agreed to furnish specific quantities of specific items at specific prices, and a deck of pre-punched cards representing these items was developed. These cards served as purchase orders for TI and as invoices for the supplier and enabled him to reorder depleted stock, as required, automatically. TI and the supplier saved countless hours of time and thousands of dollars in paperwork costs by utilizing this computerized tie-in. This particular supplier also used a random access capability for instant stock analysis. (He is a very successful supplier.) (1, vol. 16, p. 22)

The above is mentioned only as an interesting sidelight. There may be spinoffs from a computerized maintenance record-keeping system that are not apparent in a first glance. However, everything is not always so promising from installation of a computerized reporting system for maintenance. An article by Jorgenson (7) illustrates this.

> One temptation we did not avoid was to over-report. We intended to schedule our program and record equipment maintenance cost by machine component. We felt this might reveal what parts of large systems were causing excessive maintenance, and perhaps even what makes of belts, traps, valves, packing, etc., gave us the best service. The idea may be good but in our case it proved impractical. It generated reports too voluminous for realistic analysis. The approach was shortly changed to scheduling and reporting by major machine or system only. (7, p. 102)

Jorgenson (7) found that condensing the amount of material put out by the computer was the wise thing to do to make reports more usable.

> Each manager (now) receives a monthly computer printout, upon which he lists all his equipment on the program, current month's operating repairs, and plant maintenance costs, plus year-to-date figures. We need to streamline this list to an exception type report, one which will indicate only those pieces of equipment requiring attention because their operating costs fall either above or below a pre-determined level. Once we find some way to determine this level, we will be on our way to answering the big question of all maintenance organizations: What is the optimum level of plant maintenance? (7, p. 103)

A key observation from Jorgenson's quote is that even with a modern data retrieval system they still did not know what their optimum level of maintenance spending was.

The literature quoted above was mentioned to illustrate what has been theorized as possible in the way of data retrieval systems - I. E. Journal articles (8) and Turban (9), and what has actually been used - Texas Instruments (1) and Jorgenson (7). There is obviously a wide difference between what is desired and what is feasible.

Probability Distributions Common to Maintenance

Breakdown duration and frequency were estimated in this study. Since no data was available to develop a frequency distribution of the breakdowns, literature was consulted to determine the frequency distributions common to maintenance. These distributions were then used.

One important theoretical finding by R. F. Drennick (3) is concerned with the failure behavior of complex equipment:

> In theoretical studies of equipment reliability, one is often concerned with systems consisting of many components, each subject to an individual pattern of malfunction and replacement, and all parts together making up the failure pattern of the equipment as a whole. The present note is concerned with that overall pattern and more particularly with the fact that it grows the more simple, statistically speaking, the more complex the equipment. Under some reasonably general conditions, the distribution of the time between failures tends to the exponential as the complexity and the time of operation increase, and somewhat less generally, so does the time up to the first failure of the equipment. (3, vol. 8, p. 680)

Drenick goes on to comment that his theorem:

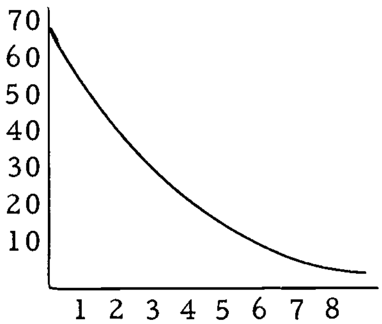
> ...asserts in effect that a complex piece of equipment, after an extended period of operation, will tend to exhibit a failure pattern with an exponential distribution for the time between failures. (3, vol. 8, p. 680)

A non-operations researcher who has had practical experience in maintenance engineering, Mann (8), supports the findings of Drenick by stating that the Mean Time Between Failures is characterized by the exponential distribution:

$Px, t = e^{-z}$ where z = mean # of failures (8, p. 564), and
x = # of machine failures that exceed a given downtime, and
t = length of downtime.

Mann continues with some very helpful mathematical generalizations which he says are "Distributions common in maintenance...", (8, p. 464) being concerned with the distribution of the number of machine failures that exceed a given downtime versus the length of the downtime;

# of machine failures that exceed a given downtime

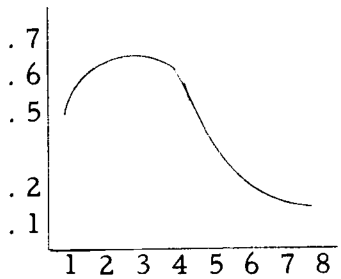


length of downtime in hours (8, p. 464)

As can be seen, breakdown times are exponentially distributed.

A second very helpful relationship listed by Mann is concerned with the manner in which a group of machines fail. This is shown in a Poisson distribution shown on the following page.

Probability of x occurring



x mean time between failure (8, p. 464)

The random variable x in this case is the mean time between failure.

Mann continues with a discussion of the similarity between maintenance and queueing:

> Maintenance is in itself a waiting line situation, that is, waiting for a facility to fail. Example: we can assume that manner in which a group of machines fail is considered to adhere to a Poisson distribution. The length of time to service the units is assumed to be exponentially distributed... The probability of x failures in time, then, is
>
> $$Px, t = \frac{z^x e^{-z}}{x!}$$
>
> where z = mean no. of failures
> x- no. of failures within time t. (8, p. 465)

Although the above seem rather elementary, the proof (especially in Drenick's work) is quite rigorous.

To give further credence to the hypothesis that the Poisson distribution applied to the occurrence of breakdowns, we find in Flagle (5) that queueing theory is usually characterized by "... a Poisson process... one characterized by a negative exponential distribution of intervals between calls. . . ". (5, p. 401). This Poisson process occurs in maintenance as:

> The classical problem of this type deals with the maintenance of a finite group of machines, each of which has some known or estimated factors characteristic of rate of chance breakdown. (5, p. 413)

In accordance with the above findings, the Poisson distribution is used in this study.

Because computer simulation is the basic analysis procedure, a literature search was conducted to find examples of simulation to aid major maintenance decisions. Nothing was found. Still, several texts on simulation were influential to this analysis and they are listed in the Bibliography.

III. DATA BASE

In many industries a vocabulary peculiar to that industry develops over the years. Such is the case at Kaiser Aluminum's plant. Before proceeding further, therefore, it is essential to define terms peculiar to Kaiser which will occur later.

List of Definitions

Ingot - a large, solid block of aluminum, usually measuring two feet thick by eight feet long by five feet wide. Ingots are cast into this form from molten aluminum. The casting is done at the aluminum plant, upstream from the Hot Line, at a production area called Remelt.

Hot Line - a group of machines which force ingots through a series of rollers, gradually pressing the ingot into a thinner and thinner piece of metal. As the aluminum ingot gets thinner, it grows longer and longer while the width remains the same. This long thin piece of aluminum is then wrapped into a coil. This coil of aluminum is still referred to as an ingot, even though it is in the form of a coil.

Four Highs - one- and two-stand tandem rolling mills which could reduce the gauge of coiled aluminum sheet from approximately .125" to a range of finished gauges from .010" to .060".

Multiple passes through a four high mill are often required to obtain the desired finished gauge. A maximum reduction of about 50% of the entry gauge is possible with a single stand four high mill pass.

Five-Stand - five tandem four high stands arranged in series in a single rolling mill; thus, performing in a single pass, the reduction in gauge which would require five single-stand passes.

Slitters - coil slitters trim the edges and/or multiple slit aluminum coiled sheet either prior to, between, or following cold rolling reductions. The objective is to both trim the often ragged edge of the sheet and to slit the product to the desired finished width and dimensional tolerances.

Cost of Lost Sales - the short term profit loss incurred when an order is cancelled. In this thesis a cancellation is considered as one which results from an excessive delay in supplying the customer with his order. For example, if a customer desires his aluminum on a certain date, and it is not available in Finished Goods Inventory, the ingot must go through the full production process. If production delays occur which lengthen the estimated time of completion beyond the order due date, the customer is notified. If an extension is not granted to Kaiser, and the customer can fill his needs elsewhere, he cancels his order. An industry-wide average of 5¢/pound short term profit is lost on such a cancellation. An average ingot weighs 6,000 pounds and hence, \$300/ingot is the lost sale cost per ingot.

Cost of Downtime - the costs which are incurred when a machine breaks down. Specifically at Kaiser these consist of:

Cost of Labor - wages paid to the machine crew while they are idle.

General Center Recharge - the cost of certain non-recoverable supplies and the "rent" of the machine as well as janitorial services. This is basically the overhead which each machine has to support.

Cost of Inventory - this is the opportunity cost that is incurred when inventory is stored. That is, the money which is tied up in inventory could be used for something else. The cost of capital used was 9%.

Cost of Breakdown Repair - this is the cost of repair each time a breakdown occurs. This cost consists of the labor of the maintenance crew, and the materials they used in the repair.

Cost of Major Maintenance Repair - this is the cost of repairing, modifying, or replacing a piece of equipment which typically suffers a large number of breakdowns. The intent in effecting this type of repair is to reduce the number of breakdowns considerably, and hopefully eliminate them completely. The cost of major maintenance repair consists of the labor and materials used.

Data and Method Currently Used at Kaiser for the Major Maintenance Decision

The first phase of this investigation was to determine the information currently available for making the major maintenance decision and the method used. This was a simple task as few records are kept of the number and duration of breakdowns. The typical pattern is for a piece of equipment to begin suffering an abnormal number of breakdowns. Each breakdown is repaired and with each repetition of the breakdown, the piece of equipment attains a greater notoriety among management personnel.

As the equipment fails, more and more often, a study is made as to the cost of major maintenance. This cost is then compared to the cost of breakdown per occurrence and the machine's downtime cost of each breakdown. The latter two costs are projected on an annual basis and this figure is treated as the annual savings available if major maintenance is performed.

A request for major maintenance is then made, based on a simple payback period. The request is sent to the plant manager if the major maintenance costs less than $10,000, or to Oakland (Corporate Headquarters) if it is over that amount.

If the information on the request is felt to be accurate, and the return on investment is high enough, authorization is given, and the major maintenance takes place.

To summarize, the major maintenance decision is made with two pieces of information: (1) cost of downtime of the machine which is breaking down, and (2) the cost of breakdown repair. Other costs which are pertinent to the single-channel major maintenance system are ignored but will be included in this study. Prior to this presentation, however, familiarity with the production facility at Kaiser is necessary.

Description of the Production Configuration Studied

To demonstrate the effects that single-channel breakdowns have on two parallel channels, attention is focused on the Remelt, Hot-Line, Cold Mills production configuration at Kaiser. The Remelt area is the upstream multiple channel, the Hot-Line is the single channel on which breakdowns are studied, and the Cold Mills are the downstream multiple channel. The following provides a brief description of the equipment modeled in the simulation program of Chapter IV. Processes which occur in the Kaiser plant but are not considered in the simulation program are also included.

The first multi-channel production area is Remelt. This area supplies the Hot-Line with ingots. Ingots of aluminum are cast out of molten aluminum in large pits called casting stations. There are several of these casting stations, all supplying ingots. The ingots are removed from the casting stations, allowed to cool and sent to an in-process inventory. Ingots are taken from this inventory and their sides are smoothed. The side of an ingot is smoothed by sawing a thin layer of metal away. This smoothing is done to minimize roll defects downstream. The machines which saw the sides of the ingot are called the scalpers and there are several of them. Ingots from the scalpers are sent to another, different in-process inventory. It should be mentioned that all inventories referred to in this work are simply stacks of ingots placed on the ground, usually in the immediate area of the processing center using the ingot as a raw material.

When the ingots are due for treatment on the Hot-Line, they are taken by crane to a heat bay which brings the ingot up to rolling temperature. The heat bay is a huge series of holes dug in the ground, the air in the holes being heated by natural gas furnaces. The heat bays are called re-heat pits and they heat the ingot to approximately $1500^{o}F$.

When the ingots reach the correct temperature and the Hot-Line is ready to process them, a crane picks up individual ingots and places them on a table in front of the Hot-Line. The table is equipped with power rollers that advance the ingot to the first rolls of the Hot-Line. The table is approximately 30 feet long.

After the ingot is wrapped into coil form at the terminus of the Hot-Line it is placed on a large tray which holds approximately 35 coils. The tray is lifted by an overhead crane and taken to the Batch Furnace. The Batch Furnace heat treats the coils of aluminum, mainly to relieve the work hardening caused by Hot-Line processing. During this heat treating the coils are left on the tray. After the heat treating process the tray is again carried by the overhead crane to the Cold Mills. The trays of coils are placed on the ground in reach of the various Cold Mill machines, thus forming the Cold Mill in-process ingot inventory.

The Batch Furnace heat treating process is not modeled in the simulation program of this study. Data indicates no significant variance in processing time at this area. Industrial engineers at Kaiser believed that the simulation need not include the Batch Furnace, hence its omission.

The Cold Mills are modeled in the simulation program. There are four Four-Highs, five Slitters and one Five-Stand in the Cold Mills.

Summary of Required Data

A variety of data is required for a study of this type. Since the usefulness of this treatise for future studies lies in the approach, a list of the type of data that must be collected is shown for future reference.

Table 1. Summary of required data.

Area	Data Needed
1. Upstream Parallel Channel	Fastest processing time through the fastest channel
2. Single-Channel	1. Average frequency and duration of breakdowns. 2. Cost of temporary and permanent repair 3. Cost of downtime 4. Delay sufficient to cause a Lost Sale 5. Production Rate 6. Monthly or annual production
3. Downstream Parallel Channel	1. Cost of Downtime 2. Cost of Inventory 3. Delay sufficient to cause a Lost Sale 4. Production rates. 5. Product flow

This list of data is only suggested as an aid to future investigations. The meaning and need for these data will become evident in future chapters. The data collected from Kaiser Aluminum are presented in the order given in Table 1 in the following sections.

Upstream Parallel Channel

Fastest Processing Time

The fastest processing time through Remelt is needed in the Poisson calculations to determine the probability that sales are lost due to Hot-Line breakdowns. Personnel at Kaiser Aluminum estimate that the fastest possible time through Remelt is approximately five days.

Single-Channel

Average Frequency and Duration of Breakdowns

The breakdowns which were studied occur on the Hot-Line. No records are kept of the average frequency and average duration of Hot-Line breakdowns. As a result they had to be developed.

Data from the operation summary of the Hot-Line indicate that in 1970 the Hot-Line suffered 16.6% downtime due to breakdowns of the equipment. That is, of the total hours that are available for production during the year, 16.6% of them were consumed by downtime. A document prepared by Kaiser Aluminum also reports that in 1970 17.3% of the available hours were consumed by operational delays, delays occurring as a result of operator errors, scheduling mistakes, etc. This report also shows that the Hot-Line was down 2.1% of the time due to lack of metal to process. In total, the Hot-Line was not producing 36% of the time.

1970 figures are the latest available data. The Hot-Line operated on a 15 shift schedule in 1970. That is, ingots were processed five days a week, three shifts per day. Currently operations are on a 20 shift schedule which consits of a seven day week, three shifts per day with one "missing" shift consumed by preventive maintenance. It is assumed that the 36% figure of 1970 is applicable to a 20 shift schedule.

Maintenance personnel were questioned as to which pieces of equipment were causing the breakdowns on the Hot-Line. They came up with a list of 20 pieces of equipment that cause breakdowns. These pieces were nicknamed the Twenty Typicals. The list of Twenty Typicals is shown in Table 2.

The table shows the name of the piece of equipment which is breaking down, the frequency per year that it breaks down and the Low, Average and High time to repair the breakdown. Low repair time occurs 10% of the time, average occurs 80% of the time and high occurs 10% of the time.

The pieces of equipment which cause breakdowns change over the years. As explained previously, when breakdowns occur often enough and cost too much, they are repaired by Major Maintenance. The Twenty Typicals are used as examples to indicate the patterns that Hot-Line breakdowns follow as far as frequency and duration of breakdown. Maintenance personnel felt that the Twenty Typicals were representative of a "standard" breakdown no matter what time period the examination took place. That is, a list of "Twenty Typicals" from 1955 would exhibit much the same behavior as that of 1970 even though the list of 1955 would not consist of the same pieces of equipment.

Table 2. List of Twenty Typicals

Name of Equipment	Freq./yr.	Time to repair (hours) Low	Avg.	High
120" Accumulator	15	.50	1.00	4.00
120" Screwdown	50	.10	.20	1.00
Stiff Leg Cranes	15	.20	.40	1.50
120" Roll Tables	15	.10	.20	4.00
120" Rolls	10	.50	1.00	1.50
Stiff Leg Pt. Chg.	360	.08	.10	.20
120" Manipulators	10	.10	.20	1.50
Stripper Universal	5	.40	.60	1.00
Lay-Off Crane	6	.50	.80	1.20
Lay-Off Crane Cables	6	.30	.40	.60
Scratch Brush	220	.50	.80	1.50
80" Mill Screwdowns	20	.10	.50	4.00
80" Mill Loopers	25	.10	.20	1.50
80" Mill Trimmer	50	.10	.30	4.00
Roll Kickout	10	.10	.50	2.00
80" Electric Kickout	15	.10	.30	3.00
Trimmer Kickout	50	.10	.20	.40
Short Conveyor Cars	15	.10	.30	2.00
Stripper Alignment	50	.10	.20	.40
Roll Centering Arm	25	.10	.20	.60
TOTAL	972			

The average breakdown duration was multiplied by the yearly frequency of breakdowns to determine whether or not the Twenty Typicals represented all the breakdowns during the year. This was done by comparing the total hours (duration of breakdown x frequency) of the Twenty Typicals with the total hours that the Hot-Line was down in 1970.

Total hours that the Hot-Line was down because of breakdowns in 1970 is simply the % Maintenance Downtime, (16.6%) times the total hours available per year, (15 shifts per week x 8 hours per shift x 52 weeks per year), or 6240 hours/year x .166. This equals approximately 1036 hours per year.

The total downtime caused by the Twenty Typicals was found by multiplying the probability of a Low, Average, or High breakdown duration by their respective duration and then multiplying this weighted average breakdown duration by its frequency per year. A sample calculation is shown below:

	Low	Average	High
120 Accumulator	.5	1	4

Weighted Average Repair Time = (.5 x .1) + (1 x .8) x (4 x .1) = 1.25 hrs.

Table 3 shows the weighted average repair time multiplied by the yearly frequency calculations to derive the hours per year consumed by Hot-Line breakdowns.

The Twenty Typicals accounted for 300 hours of downtime in 1970. There was a total of 1,036 hours of downtime in 1970. Therefore, 736 hours of downtime are not explained by the list of breakdowns developed by the maintenance personnel at Kaiser Aluminum. This is understandable as many breakdowns probably only occur once or twice a year and it is not humanly possible to recall each one of these. For the purpose of analysis in this thesis, it is assumed that the average breakdown duration, (300 hours/972 breakdowns = .309 hrs/breakdown), is typical for all breakdowns.

Table 3. Hours consumed annually by Hot-Line breakdowns.

Name of Equipment	Frequency/ yr. X	Weighted Avg. Repair Time Hrs. =	Total Hrs./yr. Consumed by Breakdown
120 Accumulator	15	1.250	18.75
120 Screwdown	50	.261	13.50
Stiff Leg Cranes	15	.390	7.35
120'' Roll Tables	15	.570	8.55
120'' Rolls	10	1.000	10.00
Stiff Leg Pt. Chg.	360	.108	38.90
120'' Manipulators	10	.32	3.20
Stripper Universal	5	.62	3.10
Lay Off Crane	6	.81	4.86
Lay Off Crane Cables	6	.41	2.46
Scratch Brush	220	.36	79.30
80'' Mill Screwdowns	20	.81	16.20
80'' Mill Loopers	25	.32	8.00
80'' Mill Trimmer	50	.65	37.50
Roll Kickout	10	.61	6.10
80'' Elec. Kickout	15	.55	8.25
Trimmer Kickout	50	.21	10.50
Short Conveyor Cars	15	.45	6.75
Stripper Alignment	50	.21	10.50
Roll Centering Arm	25	.23	5.75
TOTAL	972		299.52

The frequency per year of the breakdowns on the Hot-Line is therefore assumed to be the total hours per year of maintenance downtime divided by the average duration, or:

$$\frac{1036 \text{ downtime hrs/yr.}}{1309 \text{ hrs./breakdown}} = 3,355 \text{ breakdowns/yr.}$$

The frequency for a 20 shift operation is assumed to be: 8,320 hours/yr. (20 shifts/wk. x 8 hrs./shift x 52 wks.) times .166 (the % maintenance downtime level), divided by the average breakdown duration, or:

$$\frac{8320 \times .166}{.309} = 4,470 \text{ breakdowns/yr.}$$

Deriving the breakdown frequency per year in this fashion for a 20 shift operation implies that the duration and percentage of total operating time consumed by breakdowns does not change. Only the frequency is assumed to change. This is a logical assumption since it follows naturally that the longer you operate a piece of equipment, the greater number of breakdowns it will suffer.

Cost of Temporary and Permanent Repair

Maintenance personnel were questioned as to the cost of temporary and permanent repair. Not all the equipment is feasibly repairable and as a result, N/F appears where appropriate in Table 4. N/F stands for Not Feasible.

Table 4. Cost of temporary and permanent repair.

Name of equipment	Cost of Temporary Repair per Occurrence of a Breakdown	Cost of Permanent Repair
120" Accumulator	$1,000	$ 20,000
120" Screwdown	400	N/F
Stiff Leg Cranes	1,500	500,000
120" Roll Tables	100	N/F
120" Rolls	5,000	1,250,000
Stiff Leg Pt. Chg.	25	N/F
120" Manipulators	250	100,000
Stripper Universal	500	N/F
Lay-Off Crane	750	25,000
Lay-Off Crane Cables	500	N/F
Scratch Brush	1,500	N/F
80" Mill Screwdowns	500	N/F
80" Mill Loopers	375	N/F
80" Mill Trimmer	500	300,000
Roll Kickout	250	N/F
80" Electric Kickout	150	N/F
Trimmer Kickout	100	N/F
Short Conveyor Cars	500	112,500
Stripper Alignment	100	N/F
Roll Centering Arm	250	25,000

The eight pieces of equipment that can be permanently repaired account for approximately 1.34% of the annual Hot-Line Downtime. Repairing all eight pieces of equipment would cost $2,232,500. If all eight pieces of equipment were repaired the Hot-Line downtime level would drop from 36% to 34.66%. The portion of Hot-Line downtime caused by the eight pieces of equipment is developed below in Table 5. The total cost of repairing the eight pieces of equipment is also shown.

Table 5. Total Repair Cost and Reduction of Hot-Line Downtime.

Cost of Permanent Repair	Breakdown Name	Weighted Average Repair Time, hrs. x	Freq/ yr. =	Breakdown Hours/ yr.
$ 20,000	120 Accumulator	1.25	15	18.75
$ 500,000	Stiff Leg Crane	.49	15	7.35
$1,250,000	120" Rolls	1.00	10	10.00
$ 100,000	120" Manipulators	.32	10	3.20
$ 25,000	Layoff Crane	.81	6	4.86
$ 300,000	80" Mill Trimmer	.65	50	37.50
$ 112,000	Short Conveyor Cars	.45	15	6.75
$ 25,000	Roll Centering Arm	.23	25	5.75
$2,332,500 Total			146	84.16

$$\frac{\text{84.16 Breakdown Hours/yr.}}{\text{6,210 Available Hours/yr.}} = 1.34\%$$

Cost of Downtime

Cost of Downtime is the expense incurred when a machine suffers a delay in production. When a delay occurs, the machine's crew is idle. Since the machine is not producing, overhead charges which the machine must support are not being paid.

A distinction must be made between the Cost of Breakdown Repair and the Cost of Downtime. Cost of Breakdown Repair is the labor and materials required to repair a machine which has broken down. Cost of Downtime is the cost incurred because a machine is idle. A machine can be made idle for several reasons such as operator errors, no metal to work with, or a breakdown. These two costs are distinct and not identical.

When a machine suffers downtime the foreman of the machine makes an effort to determine how long the machine will be idled. If he feels that the delay will be lengthy, he attempts to place the machine's idle crew elsewhere in order to give them productive work. Other work is not always available, however, and this study uses two costs of Downtime:

1. The Cost of Downtime incurred when a machine's crew can be used elsewhere[7].
2. The Cost of Downtime incurred when a machine's crew cannot be used elsewhere[8].

---

[7]This condition is defined as "Best Case" and will be understood as such when referred to subsequently.

[8]This condition is defined as "Worst Case" and will be referred to as such later.

The labor portion of downtime comprises the bulk of the Cost of Downtime. Overhead charges do make up an important element of the Cost of Downtime, however, and must be examined.

Overhead is comprised of two costs: "Machine Rent" and "General Center Recharge". Machine Rent is the depreciation cost of a machine, computed at an hourly rate. General Center Recharge is the portion of plant overhead for which a machine is accountable. General Center Recharge includes such things as lighting, heat, and janitorial services. General Center Recharge is also computed at an hourly rate.

Listed in Table 6 is the Hot-Line Cost of Downtime per hour. The Best Case Rate is simply overhead, while Worst Case Rate is overhead plus labor.

Table 6. Hot-Line Cost of Downtime per hour.

	$Cost/Hr.
Hot-Line	
Labor	118
Machine Rent	40
General Center Recharge	22
TOTAL	$190
Best Case Rate	62
Worst Case Rate	190

Delay Sufficient to Cause a Lost Sale

Plant industrial engineers were questioned as to the amount of delay required at the Hot-Line to precipitate a Lost Sale. The general consensus was that if more than 24 hours worth of breakdowns occurred within any given five-day period, a sale would be lost. The five-day period is the fastest processing time at the upstream parallel channel.

Production Rate

The Hot-Line production rate is derived from a figure developed by the Planning Department at Kaiser Aluminum. The Planning Department computes the hours per ingot production rate of the Hot-Line. This figure is the actual processing time and does not include any delays. It is the time spent actually processing ingots divided by the number of ingots. This production rate is 4.23 minutes per ingot.

Monthly Production

The Hot-Line produces an average of 6,000 ingots per month. The Cold Mills receive 5,000 ingots per month while the other 1,000 ingots go to process lines not considered in this study. The 1,000 ingots not sent to the Cold Mills are produced at random by the Hot-Line.

Downstream Parallel Channel

The Cold Mill is the downstream parallel channel. Presented below are the data collected for this work.

Cost of Downtime

The best and worst case downtime costs per hour for the Cold Mill machines are shown in Table 7. Since the Four-Highs each have different costs, they are listed individually.

Table 7. Cold Mill Best and Worst Case Downtime costs.

Production Facility	Best Case Downtime Cost, $ per hour	Worst Case Downtime Cost, $ per hour
Four-High #1	9.65	56
Four-High #2	7.73	47
Four-High #3	36.00	70
Four-High #4	17.00	41
Five-Stand	57.00	97
Slitters (each)	17.00	31

Cost of Inventory

Cost of Inventory is the opportunity cost of keeping in-process inventory. Opportunity cost is the rate of return which could be earned with the money tied up in inventory if it were invested elsewhere. The rate of return is assumed to be 9%, the estimated Cost of Capital at Kaiser Aluminum.

Kaiser has approximately 15¢ per pound invested in each ingot by the time it reaches the Cold Mills. The Cost of Inventory is developed only for the Cold Mills.

An average ingot weighs 6,000 pounds. An average ingot therefore represents an investment of $900 when it is in the Cold Mill In-Process Inventory.

6,000 lb./ingot x 15¢/lb. = $900/ingot

At 9% annual interest rate each ingot costs $6.75 per month.

$$\$900/\text{ingot} \times \frac{9\%/\text{yr.}}{12 \text{ mo./yr.}} = \$6.75/\text{mo. for each ingot}$$

Delay Sufficient to Cause a Lost Sale

Plant personnel were questioned as to the length of delay at the Hot-Line necessary to cause a Cold Mill Lost Sale. Their estimate was a delay of six days or 144 hours.

Fastest Processing Time

The fastest time that an ingot can pass through the Cold Mills is 20 days. This figure is used in the Poisson calculations.

Production Rates

The production rates of the various Cold Mill machines were taken from the Planning Department's actual hours per ingot computed for the Five-Stand, Slitter and Four Highs. The actual hours per ingot figures were inflated by a factor to account for Cold Mill Operational and Breakdown delays. Out-of-metal delays were not incorporated into the production rates as this affect is the one that the simulation program attempts to determine. Planning personnel estimated operational and out-of-metal delays consumed approximately 4.8% of the time available for production. The average hours per ingot are therefore divided by .952 to get the production rates shown in Table 8 representing operational and out-of-metal delays.

Table 8. Simulation production rates.

Machine	Avg. Actual Hrs. per ingot	÷	Factor	=	Production Rate Used
Four Highs	.241		.952		.253 hrs./ingot
Five Stand	.314		.952		.331 hrs./ingot
Slitters	.682		.952		.717 hrs./ingot

Product Flow

As mentioned, the Hot-Line averages 5,000 ingots/mo. for the Cold Mills. Ingots are sent downstream to the Cold Mills in the following fashion: 2,500 ingots per month go to the Four-Highs, are processed there and sent to the Slitters; 2,000 ingots per month are sent to the Five-Stand and of these 1,500 are sent to the Slitters after processing; 500 ingots per month go straight to the Slitters.

Cold Mill monthly production rates are shown in Table 9.

Table 9. Cold Mill production rates.

Area	Ingots/mo.
Hot-Line	5,000
Four-Highs	2,500
Five-Stand	2,000
Slitters[1]	500
Slitters[2]	4,000

[1] 500 ingots are sent directly to the Slitters from the Hot-Line.

[2] 4,000 ingots are sent to the Slitters from the Four-Highs and Five-Stand.

The unexplained 500 ingots per month processed at the Five-Stand are sent to areas downstream which are not included in the study. Figure 2 shows the product flow.

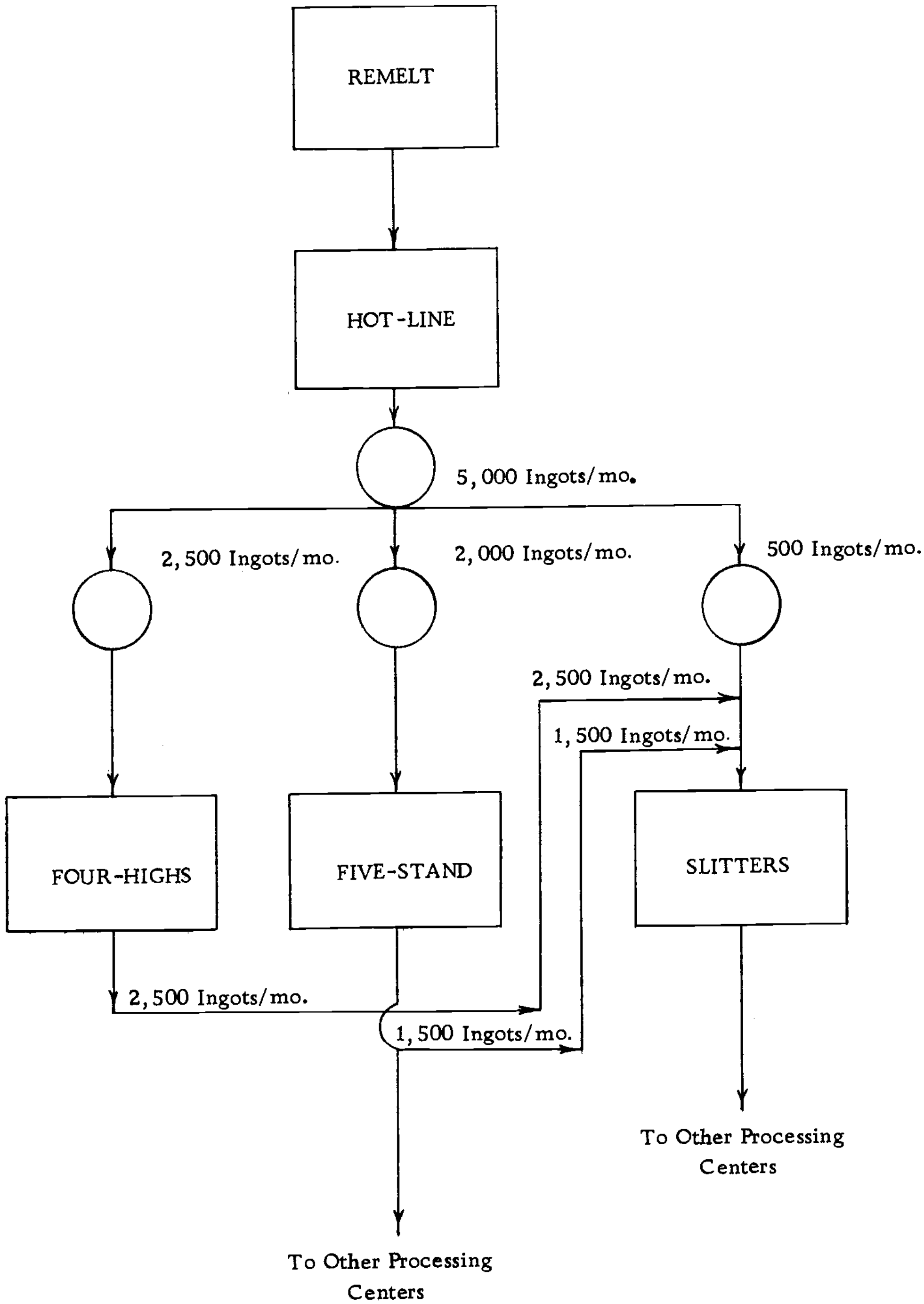


Figure 2. Product flow.

IV. THE SIMULATION PROGRAM

Description of the Program

A computer simulation program was written to determine the delay costs occurring at the Cold Mills as a result of Hot-Line Downtime. A brief description of the simulation language is presented below, accompanied by a description of the Cold Mills and how the computer simulates their operation.

The simulation language used was GPSS, General Purpose Simulation System, a language developed by IBM. This language was found to be very adaptable to the purpose of this thesis. The data that the GPSS program automatically prints out supplies nearly everything that is necessary to compute costs, facility usage, etc.

The Hot-Line is the beginning production facility of the simulation program. Ingots are produced here at varying production rates. These production rates were determined from the 4.23 minutes/ingot figure previously presented. Development of the varying production rate figures will be explained after a description of the simulation program.

Hot-Line output is sent to the simulation program's Cold Mills. The computer records the average time that ingots remain in inventory and the average processing time. The computer also tallies the average in-process inventory in front of the individual areas of the Cold

Mills (Four-Highs, Five-Stand, etc.). The average inventory for each of these is printed out at the end of the run and used in determining the annual inventory cost.

The average usage of each of the processing centers of the Cold Mill is also recorded. These usage figures are used in computing the cost of breakdown delays. For example, a facility usage of 20% would indicate that the facility in question was out of metal and not used 80% of the month. Remember that all other Cold Mill delays have been compensated for in their production rates and as a result the only cause of Cold Mill downtime is out-of-metal delays caused by Hot-Line breakdowns. A flow chart and copy of the program are shown in Appendix B and C, respectively.

Experimentation Through Variation of Simulation Program Single-Channel Production Rate

The simulation program was designed to test the affect that Hot-Line Breakdowns have on the Cost of Downtime and Cost of Inventory in the Cold Mills.

The reader will recall that the Hot-Line production rate averages 4.23 minutes per ingot. Simulation runs were performed at various levels of Hot-Line Downtime. The runs were conducted at levels from 15% Hot-Line Downtime to 50% in 5% increments. It should be noted that the simulation program's Hot-Line Downtime includes all Downtime causing factors on the Hot-Line. These are:

1. out of metal delays (2.1% in 1970),
2. operational delays (17.3% in 1970), and
3. breakdown delays (16.6% in 1970).

TOTAL 36.0%

Since the current level of Hot-Line Downtime is 36% or approximately 35%, it is felt that by running the simulation program from 20% to 50% delay levels closely parallels the effect of going from 0% to 30% Hot-Line Breakdown Downtime.

The Hot-Line production rate of the simulation program was varied to represent the various levels of Hot-Line Downtime. A Hot-Line production rate of 4.23 minutes per ingot was used as a "base" rate. The production rate was varied by dividing 4.23 minutes/ingot by the corresponding uptime for each delay or downtime level. For example, 95% uptime corresponds to 5% downtime. A sample calculation is shown. The Hot-Line production rate is calculated to be 6.05 minutes per ingot at the 30% Hot-Line delay level. There are 8,320 hrs./yr. available for production:

20 shifts/wk. x 8 hours shift x 52 weeks/yr. = 8,320 hours/yr. available for Hot-Line production.

If the Hot-Line suffered 30% production delays only 5,825 hours would be available for production per year.

8,320 - (.30 x 8,320) = 5,825 hours

82,500 ingots would be produced at the 30% Hot-Line delay level:

$$\frac{5,825 \text{ hours x } 60 \text{ min.}}{4.23 \text{ ingots/hr.}} = 82,500 \text{ ingots/yr.}$$

Putting this on an annual basis we find that the new production rate would be 6.05 minutes per ingot:

$$\frac{8,320 \text{ hrs. x } 60 \text{ min.}}{82,500 \text{ ingots/yr.}} = 6.05 \text{ min./ingot.}$$

The same rate of 6.05 min. /ingot can be found by simply dividing 4.23 ingots by 70%:

$$\frac{4.23 \text{ min. /ingot}}{100\% - 30\%} = 6.05 \text{ minutes/ingot.}$$

The production rates that were used in the simulation program to represent Hot-Line delays from 15% to 50% are listed below in Table 10.

Table 10. Simulation production rates.

Hot-Line Delay Level by 5% Increments	Production Rate Minutes/Ingot
15	5.0
20	5.3
25	5.6
30	6.0
35	6.5
40	7.1
45	7.7
50	8.5

Two runs of the simulation program were made at each level of Hot-Line downtime. The first run at each level simulates operation of the Hot-Line and Cold Mills for 1/20 of a month. The second run at each level simulates operation for 1/10 of a month. The program would not simulate for a longer period of time as computer storage capacity is exceeded beyond 1/10 month simulation.

To study the effect of initial conditions and to verify that the simulation has reached its steady state condition, the 1/10 month simulation statistics were compared to the 1/20 month statistics. For example, the average utilization of the Five-stand at 40% Hot-Line downtime level was .9903 (table 11, p. 46), while the 1/20 month statistic for the same run was .9901. If $\bar{x}_1$ is the average utilization for the 1/10 month run and $\bar{x}_2$ the average utilization for the 1/20 month run then $\bar{x}_2$ is within the set of $\bar{x}_1$. What is needed is $\bar{x}'_1$, the equivalent of $\bar{x}_2$. Since $\bar{x}'_1 = 2\bar{x}_1 - \bar{x}_2$, the confidence interval can be computed from the standard deviation formula:

$$S = \sqrt{\frac{(\bar{x}'_1 - \bar{\bar{x}})^2 + (\bar{x}_2 - \bar{\bar{x}})^2}{n - 1}}$$

where; $\bar{x}'_1 = 2\bar{x}_1 - \bar{x}_2 = 2(.9903) - (.9901) = .9905$

$\bar{x}_2 = .9901$

$$\bar{\bar{x}} = \frac{\bar{x}'_1 + \bar{x}_2}{2} = \frac{(2\bar{x}_1 - \bar{x}_2) + \bar{x}_2}{2} = \bar{x}_1 = .9903$$

and

$$S = \sqrt{\frac{(.0002)^2 + (.0002)^2}{1}} = .00028.$$

Three S therefore equals .00084, which is approximately .08% variance at this level. This and other similar statistics verify the fact that the conclusions of the following chapters are not significantly affected by statistical errors introduced in the simulation.

V. ANALYSIS

Downstream Parallel Channel Cost Analysis

Cost of Cold Mill Downtime

Cold Mill downtime caused by Hot-Line Delays is the first area examined. Simulation results for the Five-Stand shown in Table 11 reveal the average utilization of the Five-Stand and the average processing time for the 1/10 month steady-state runs. Average processing time is the average time to load, run and unload an ingot.

Table 11. Five-Stand utilization.

	Hot-Line Downtime Level							
	15%	20%	25%	30%	35%	40%	45%	50%
Average Utilization	.9955	.9916	.9928	.9912	.9911	.9903	.9463	.8096
Average Processing Time in minutes	19.7	19.8	19.8	19.7	19.7	19.8	19.6	19.6

Full utilization of a facility is 1.00. As the reader can see, the Five-Stand does not begin dropping below 99% utilization until the Hot-Line reaches a 45% downtime level. Table 12 shows the number of hours delay occurring at the Five-Stand at each level of downtime. An example calculation explains the costs shown in Table 12. The Hot-Line at a 45% Delay (Downtime) level causes a 94% utilization of the Five-Stand or, in other words, a 6% delay level. A 6% delay level represents a loss of 500 hours of production time annually at the Five-Stand:

20 shifts/wk. x 8 hours/shift x 52 weeks/hr. = 8, 320 hrs/yr.

8, 320 [hrs./yr. available for Five-Stand production] x .06
[Delay level caused by Hot-Line Delays] = 499.20 hours lost

or

500 hours lost to delays.

Using the best and worst case downtime cost rates, the loss of 500 hours/yr. on the Five-Stand costs $48, 500 annually:

500 hrs x $57/hr. [Best Case rate] = $28, 500 annual cost for the best case, and

500 hrs x $97/hr. [Worst Case rate] = $48, 500 annual cost for the worst case.

The method shown above is used in Table 12.

Table 12. Five-Stand marginal savings.

Level of Downtime	Average Use of the Five-Stand	100% Average Utilization	Multiplied by hrs/yr available	Hrs/yr consumed at the Five-Stand due to Hot-Line Delays
15%	.99	.01	8,320	Not meaningful
20%	.99	.01	"	"
25%	.99	.01	"	"
30%	.99	.01	"	"
35%	.99	.01	"	"
40%	.99	.01	"	"
45%	.94	.06	"	500
50%	.81	.19	"	1,580

Downtime Level	Hrs Lost annually	Annual cost best case	Annual Marginal Savings	Annual cost worst case	Annual Marginal Savings
50%	1,580	$90,000		$154,900	
45%	500	$28,500	$61,500	$48,500	$154,900
40%	0	0	$28,500	0	$48,500

The annual marginal savings column is of interest. This column shows the annual savings available at the Five-Stand if Hot-Line delays were reduced to the levels indicated. By reducing Hot-Line Delays from 50% annually to 45% annually it would be possible to save between \$61,500 and \$154,900 annually. \$61,500 is the savings possible if the Five-Stand crew can be put to use elsewhere when the Five-Stand is out of metal, while \$154,900 represents savings possible if the crew can never be reassigned. The reader can see that no savings are available below the 40% Hot-Line Downtime level.

The Hot-Line currently suffers total downtime of approximately 35%, so no savings would be realized at the Five-Stand if Hot-Line Downtime were reduced from current levels.

The Four-Highs are the next area of interest. The reader will recall that there are four Four-High mills. The Four-Highs operate on a 15 shift schedule or five days per week, three shifts per day. The simulation program was based on a 20 shift schedule. If the simulation program modeled four Four-Highs for 20 shifts, the simulation results would be unrealistic as the Four-Highs would have 20 extra machine shifts per week:

4 machines x 20 shifts	= 80 machine shifts/wk.
-4 machines x 15 shifts/wk.	= <u>60</u> machine shifts/wk.
Total extra shifts	20 machine shifts/wk.

For this reason, only three Four-Highs were used in the simulation program, as 3 machines x 20 shifts = 60 machine shifts.

The Four-Highs are very underutilized at even the lowest levels of Hot-Line Downtime. Table 13 shows the average number of machines running out of a possible three and the average processing time.

Table 13. Four-High utilization.

	Hot-Line Downtime Level							
	15%	20%	25%	30%	35%	40%	45%	50%
Avg. No. machines used	1.50	1.45	1.32	1.30	1.15	1.08	.99	.93
Avg. Processing time in min.	15.1	15.1	15.1	15.1	15.1	15.2	15.1	15.1

The number of hours delay and marginal gain in reducing Hot-Line Downtime are not as easy to calculate as those for the Five-Stand. This is due to two factors: one, the computer's average number of machines used must be converted to a four machine, 15 shift basis and two, this conversion changes the best and worst case cost application.

The average number of machines used on a 20 shift schedule must be converted to a 15 shift schedule. For example, 1.50 machines on a 20 shift schedule equals 2.00 machines on a 15 shift schedule.

1.50 machines x 20 shifts = 30.00 machine shifts

$$\frac{30.00 \text{ machine shifts}}{15 \text{ shifts}} = 2.00 \text{ machines}$$

The average number of machines used is converted to a 15 shift basis in Table 14.

Table 14. Average number of Four-Highs . 15 shifts.

Down-time Level	Avg. No. Machines used on 20 shift schedule	x 20 shifts ÷ 15	= Avg. No. Machines used on 15 shift schedule
15%	1.50	30.0	2.00
20%	1.45	29.0	1.93
25%	1.32	26.4	1.76
30%	1.30	26.0	1.73
35%	1.15	23.00	1.53
40%	1.08	21.60	1.44
45%	.99	19.80	1.32
50%	.93	18.60	1.24

Since the average number of machines used never rises above two, the best and worst case costs are applied differently. The two unused machines are assumed to be "moth-balled" year around and the other machines used constantly. Two machines are therefore given the "Best Case" rate for all levels past 15%. The two machines with the lowest operating cost are assumed to be the machines which are not moth-balled. These are Four-High #2 and #4. Four-Highs #1 and #3 are assumed to be moth-balled at Hot-Line downtime levels higher than 15%. The marginal savings in reducing Hot-Line Downtime is shown in Table 15.

Table 15. Four-High marginal savings.

Down-time Level	Avg. No. Machines used on a 15 shift basis	2 - Avg. # 2 machines in moth-balls	Hrs Avail. for[1] annual production	Hours lost annually due to Hot-Line Downtime
15%	2.00	.00	6,240	0
20%	1.93	.07	"	437
25%	1.76	.24	"	1,490
30%	1.73	.27	"	1,685
35%	1.53	.47	"	2,930
40%	1.44	.56	"	3,490
45%	1.32	.68	"	4,250
50%	1.24	.76	"	4,740

Down-time Level	Annual Hrs. lost at Four-Highs due to Hot-Line Downtime	x Best rate of $7.73(4-Hi#2 is shut down first) = annual cost of downtime	Annual Marginal Savings from reducing Hot-Line Downtime	x Worst case Rate of $47 = Annual Cost of Downtime	Annual Marginal Savings from reducing Hot-Line Downtime
50%	4,740	$36,600		$222,500	
45%	4,250	$32,800	$3,800	$199,500	23,000
40%	3,490	$27,000	$5,800	$164,000	35,500
35%	2,930	$22,650	$4,350	$137,500	26,500
30%	1,685	$13,020	$9,630	$ 79,200	58,200
25%	1,490	$11,500	$1,520	$ 70,000	9,200
20%	437	$ 3,380	$8,120	$ 20,300	49,700
15%	0	0	$3,380	0	20,300

[1]Hours available for annual production is:

15 shifts/wk. x 8 hours/shift x 52 wks./yr. = 6,240 hrs./yr.

Savings are apparently available at the Four-Highs at every level of Hot-Line downtime. If it is assumed that the marginal savings between Hot-Line Downtime levels are linear, then $7,128 per year can be saved (using worse case costs) at the Four-Highs by reducing Hot-Line Downtime from 36% (the current level) to 34.66% (the level attainable by repairing the Eight Typicals[9]). Using best case costs, $1,166 can be saved per year. Annual marginal gain from 40% Hot-Line Downtime to 35% is $26,500 at worst case rates and $4,350 at best case rates. The savings by percentage point are $5,320 in the worst case and $870 in the best case:

worst case: $\frac{\$26,500}{5\%}$ = $5,320 annual savings per percentage point decrease in Hot-Line Downtime,

and

best case: $\frac{\$4,350}{5\%}$ = $870 annual savings per percentage point decrease in Hot-Line Downtime.

A 1.34% reduction in Hot-Line Downtime by repair of the Eight Typicals therefore saves:

1.34 x $5,320/% pt. = $7,120 in the worst case, and

1.34 x $870/% pt. = 1,166 in the best case.

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[9] The eight pieces of equipment on the Hot-Line which can be permanently repaired are referred to as the Eight Typicals. If the Eight Typicals were repaired, Hot-Line downtime would be lowered by 1.34%, hence the drop from 36% to 34.66%.

The Slitters are the last Cold Mill area requiring examination. The Five machines are operated on a 20 shift basis. Table 16 shows the average number of machines utilized at each level of downtime and the average processing time.

Table 16. Slitter utilization.

	Hot-Line Downtime Level							
	15%	20%	25%	30%	35%	40%	45%	50%
Avg. no. of Slitters Utilized	4.94	4.93	4.91	4.90	4.88	4.85	4.81	4.64
Avg. Processing time per ingot in minutes	42.7	42.5	42.3	42.6	42.4	42.6	42.4	42.4

The Best Case downtime cost for one Slitter is $17 and the Worst Case rate is $31. Table 17 shows the Marginal Gain in Reducing Hot-Line Downtime.

To obtain the Annual Marginal Savings available by reducing Hot-Line Downtime from 36% to 34.66%, linearity between the 5% Hot-Line Downtime Levels is again assumed. Reduction of Hot-Line Downtime from 36% to 34.66% saves $2,064 annually at the Slitters using Worst Case costs and $1,129 annually using Best Case costs.

The savings by percentage point are $1,154 in the Worst Case and $843 in the Best Case:

$$\frac{\$7,700}{5\%} = \$1,540\text{/percentage pt. decrease in Hot-Line downtime,}$$

and

Table 17. Slitter marginal savings.

Hot-Line Downtime Level	Avg. No. of Slitters used on a 20 shift schedule	5-Avg. # Used		x Hrs. Available for Slitter Production[1]	=	Hours Lost Annually Due to Hot-Line Downtime
15%	4.94	.06	x	8320	=	499
20%	4.93	.07	x	8320	=	582
25%	4.91	.09	x	8320	=	749
30%	4.90	.10	x	8320	=	832
35%	4.88	.12	x	8320	=	998
40%	4.85	.15	x	8320	=	1248
45%	4.81	.19	x	8320	=	1580
50%	4.64	.36	x	8320	=	2990

Downtime Level	Hours Consumed at Slitters due to Hot-Line Downtime	x Best Case Rate of $17 Equals Annual Cost	Annual Marginal Savings	x Worst Case Rate of $31 Equals Annual Cost	Annual Marginal Savings
50%	2990	$50,800		$92,600	
45%	1580	$26,850	$23,950	$49,000	$43,600
40%	1248	$21,190	$ 5,660	$38,650	$10,350
35%	998	$16,980	$ 4,210	$30,950	$ 7,700
30%	832	$14,120	$ 2,860	$25,800	$ 5,150
25%	749	$12,700	$ 1,420	$23,190	$ 2,610
20%	582	$ 9,890	$ 2,810	$18,020	$ 5,170
15%	499	$ 8,475	$ 1,415	$15,450	$ 2,570

[1] The hours available for production are the same as those used for the Five-Stand.

$\frac{\$4,210}{5\%}$ = \$843/percentage pt. decrease in Hot-Line downtime.

A 1.34% reduction in Hot-Line downtime by repair of the Eight Typicals therefore saves:

1.34 x 1,540/% pt. = \$2,064 in the worst case, and

1.34 x \$843/% pt. = \$1,129 in the best case.

A summary of the annual savings possible in the Cold Mills by the reduction of Hot-Line Downtime by repair of the Eight Typicals (from 36% to 34.66%) is shown in Table 18.

Table 18. Cold Mill downtime savings summary.

Area	Worst Case Annual Savings	Best Case Annual Savings
Five-Stand	none	none
Four-Highs	\$7,128	\$1,166
Slitters	\$2,064	\$1,129
TOTAL/YR	\$6,860	\$1,713

Cost of Cold Mill Inventory

Cost of Cold Mill inventory is the next cost examined. Since the simulation program only ran for 1/10 month at the longest, it is not possible to simply look at the simulation results and state that In-Process Inventory figures represent those of one month's production. Interpretation is essential.

The program was written to simulate operation of the Hot-Line and Cold Mills without any initial inventory. An inventory is created in front of each production center because the Hot-Line can produce ingots faster than the Cold Mills can use them.

The inventory statistics from the simulation run therefore do not represent the inventory levels that currently occur in the plant.[10] What they do show is the point at which the Hot-Line is supplying just as many ingots as the Cold Mills can use. This point is determined by comparing the 1/10 and 1/20 month average inventory for each level of Hot-Line Downtime in Table 19.

Table 19. Simulation average inventory levels.

	Hot-Line Downtime Level							
	15%	20%	25%	30%	35%	40%	45%	50%
			Five-Stand Average Inventory					
1/20 mo.	22.24	20.26	17.86	11.58	11.00	8.87	1.63	.94
1/10 mo.	47	44	36.46	23.39	23.05	15.07	2.47	1.73
			Four-High Average Inventory					
1/20 mo.	.01	0	0	0	0	0	0	0
1/10 mo.	0	0	0	0	0	0	0	0
			Slitter Average Inventory					
1/20 mo.	34.9	35.3	28.6	25	11.6	5.31	1.7	.95
1/10 mo.	83.4	71.3	58.2	53.4	25.6	11.6	2.9	.80

[10] Historical Ingot Inventory Levels are shown in Appendix D.

The point at which the Hot-Line begins falling behind the Cold Mills is that point at which the 1/10 month steady state average inventory is less than double the 1/20 month average inventory.

The logic behind this reasoning is that in the 1/20 month simulation a large surge of ingots hits the Cold Mills. If the Cold Mills are unable to keep up, the inventory, or ingots waiting for Cold Mill processing, increases in a linear fashion. If the Cold Mills are unable to keep up, the average Cold Mill inventory at 1/10 month should be at least twice that of the 1/20 month level.

Examination of Table 19 shows that the Four-Highs, with all but zero inventory at all levels of Hot-Line downtime, can stay far ahead of the Hot-Line. The Hot-Line does not begin falling behind the Five-Stand and Slitters until it (the Hot-Line) is at the 45% Downtime Level.

Since the Hot-Line operates currently at the 36% Downtime level the Five-Stand and Slitters could possibly run without any inventory at all. Examination of the monthly In-Process Ingot Inventory levels in Appendix D indicates that this is not the case, and that all the Cold Mills maintain high inventory levels.

The average Cold Mill inventory is 1,424 ingots. This inventory costs approximately $115,344 per year:

1,424 ingots x $6.75/ingot-month x 12 mo./yr. = $115,344.

It is assumed that in-process inventories are maintained in front of the Five-Stand and Slitters to prevent Lost Sales. Many of the coils of aluminum in the Cold Mill in-process inventory are multi-purpose. That is, they can be used for beer cans or mobile homes, depending on how they are processed in the Four-Highs, Five-Stand and Slitters. It only makes sense to hold some ingots in front of the Cold Mills. If an ingot suffers delays at Remelt and the Hot-Line, a sale might be lost. A Cold-Mill in-process inventory could be substituted for the delayed ingot to meet the customer's deadline, thus avoiding a Lost Sale.

If the Eight Typicals[11] were permanently repaired, the Hot-Line Downtime level would be reduced from 36 percent to 34.66 percent. With less downtime more ingots could be produced. With the Hot-Line supplying more ingots to the Cold Mill, the in-process inventory of the Cold Mill could be reduced in size.

There are 499,200 minutes available for production at the Hot-Line each year:

20 shifts/wk. x 52 wk./yr. x 480 min./shift = 499,200 min./yr.

At 36 percent Hot-Line Downtime, 179,712 minutes are consumed annually by downtime, leaving only 319,488 minutes available for

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[11] The eight pieces of equipment listed in Table 14 which can be permanently repaired are referred to as the Eight Typicals. Permanent repair of the Eight Typicals reduces the Hot-Line Downtime by 1.34%.

production:

499,200 min./yr. - (499,200 min./yr. x 36% downtime) =

319,488 min./yr.

At 34.66 percent downtime there are 326,277 min./yr. available for Hot-Line production:

499,200 min./yr. - (499,200 min./yr. x 34.66% downtime) =

326,277 min./yr.

With more production time the Hot-Line can produce 1,700 more ingots annually at the 34.66 percent downtime level than it could at the 36 percent level:

$$\frac{319,488 \text{ min./yr.}}{4.23 \text{ min./ingot}} = 75,500 \text{ ingots/yr. at the } 36\% \text{ level}$$

$$\frac{326,277 \text{ min./yr.}}{4.23 \text{ min./ingot}} = 77,200 \text{ ingots/yr. at the } 34.66\% \text{ level, and}$$

77,200 - 75,500 = 1,700 ingots/yr.

The reader will recall that of the 6,000 ingots produced per month at the Hot-Line, 5,000 go to the Cold Mills and 1,000 go to areas not considered in this analysis. For this reason only 5/6 of the 1,700 ingots would be available at the Cold Mills and this would equal 1,418 additional Cold Mill ingots:

5/6 x 1,700 ingots/yr. = 1,418 additional Cold Mill ingots.

The average monthly Cold Mill inventory level could be reduced by 158 ingots:

$$\frac{\text{1,418 additional ingots/yr.}}{\text{12 mo./yr.}} = \text{158 ingots/mo.}$$

Repair of the Eight Typicals would therefore save $12,798 per year in Cold Mill inventory cost:

158 ingots x $6.75/mo. inventory cost x 12 mo./yr. = $12,798.

Cost of Cold Mill Lost Sales

Cold Mill Lost Sales is the last Cold Mill cost to be examined. As shown in the data collection portion of this work, plant personnel estimate that if an ingot suffers more than six days worth of delays in passing through the Cold Mills, a lost sale will occur. An ingot usually takes 20 days to pass through the Cold Mills and many of the delays that an ingot suffers occur there. Hot-Line breakdowns would contribute to the six days necessary to cause a lost sale if the breakdowns held up the operation of the Cold Mills.

As seen in the Cost of Cold Mill Downtime section, the Hot-Line does not begin delaying the Cold Mills until it (the Hot-Line) reaches a 45 percent downtime level. Theoretically, therefore, at the current level of Hot-Line downtime the Hot-Line will not contribute to the six days delay necessary for a Cold Mill Lost Sale. However, for the sake of analysis it is interesting to determine the effect that Hot-Line breakdowns would have on the Cold Mill if no In-Process ingot inventory were stored there.

The effect of Hot-Line breakdowns can be determined if two assumptions are made: first, that no in-process ingot inventory is stored at the Cold Mills, and second, that 1/6 of the Hot-Line production going to areas other than the Cold Mills has no effect. The 1/6 non-Cold Mill production does have an effect but it is ignored. One-sixth of the Hot-Line production going to areas other than the Cold Mills would actually increase the effect that Hot-Line breakdowns would have on Cold Mill Lost Sales since the "gaps" in the product flow caused by breakdowns would be wider. Not only would there be breakdown "gaps," there would also be non-Cold Mill ingot "gaps."

It is difficult to determine the effect that the non-Cold Mill "gaps" would have. Consequently, the effect of Hot-Line breakdowns is computed without taking them into account. The reader is reminded, however, that the effect of Hot-Line breakdowns on Cold Mill Lost Sales would be even greater than calculated.

The probability of a total of six days or 144 hours worth of downtime occurring on the Hot-Line in a 20-day (480 hr.) period is .165 using a Hot-Line downtime level of 36%.

At 36% there are 160 breakdowns on the Hot-Line every 240 hours, or .67 every hour.[12] A total of 467 breakdowns would have to occur on the Hot-Line within 20 days to cause Cold Mill Lost Sales.

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[12]This figure is developed in the section on Cost of Hot-Line Lost Sales, Chapter V.

$$\frac{144 \text{ hrs}}{.309 \text{ hrs./breakdown}} = 467 \text{ breakdowns}$$

467 breakdowns in 480 hours is equivalent to .972 breakdowns in one hour. The probability that Hot-Line breakdowns will cause Cold Mill Lost Sales is then approximately:

$$P, 97, 100 \text{ hrs.} = \frac{67^{97} e^{-67}}{97!} = .165$$[13]

Projected on an annual basis this represents a loss of $3,730,000:

75,500 ingots/yr. x .165 x $300/ingot = $3,730,000

If the Eight Typicals were repaired, there would be 1,418 more ingots available for the Cold Mills each year. If the average Cold Mill inventory were allowed to increase by 158 ingots (instead of reducing the inventory by that amount as was seen in the previous section), then $425,400 in Lost Sales could be saved annually. This savings assumes that the additional ingots available at the 34.66 percent Hot-Line downtime level would prevent an equivalent number of lost sales:

1,418 less lost sales x $300/lost sale = $425,400.

The net savings would be $412,602 since a cost of $12,798 would be incurred when storing the additional inventory.

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[13] The use of this probability distribution is explained in the cost of Hot-Line Lost Sales section of Chapter V.

As shown, a tremendous number of ingots would suffer Lost Sales if no in-process ingot inventory were stored at the Cold Mills. Storage of an in-process inventory is much cheaper than repair of the Hot-Line's Eight Typicals to prevent Lost Sales and therefore only the inventory savings of the previous section are claimed for repair of the Eight Typicals.

Summary of Cold Mill Costs

A summary of the money that could be saved at the Cold Mills by repairing the Eight Typicals is shown in Table 20 below.

Table 20. Summary of possible Cold Mill savings.

Category of Savings	Area	Annual Savings Worst Case	Annual Savings Best Case
Downtime	Five-Stand	none	none
	Four-Highs	$7128	$1166
	Slitters	$2064	$1129
Lost Sales	All Cold Mill	0	0
Inventory		$12,798	$12,798
TOTAL		$21,990	$16,093

This range of possible savings is very small compared to those available at the Hot-Line, as will be seen.

Single-Channel Cost Analysis

Cost of Hot-Line Downtime

The first cost to be examined is that of single-channel downtime. The Hot-Line crew is usually not sent to other areas when it suffers downtime. Supervisors feel that the Hot-Line is too critical to the plant's operations to suffer a delay by waiting for recalled employees. For this reason only the worst case costs are used in computing Hot-Line cost of downtime.

The Hot-Line costs $190 per hour when it is down. This cost occurs no matter what causes the downtime. The reader will recall that the Hot-Line suffered at 36% downtime level in 1970. Since this work deals with the savings available by reducing Hot-Line breakdowns, the possible savings in going from 36% to 34.66% Hot-Line downtime are listed. This reduction of downtime closely parallels the reduction in downtime possible if all of the Eight Typicals were repaired or modified.

The savings possible by reducing overall Hot-Line Downtime from 50% to 15% are presented in Table 21. They are listed for future reference. As can be seen, $19,000 can be saved annually by reducing Hot-Line downtime from 36 to 34.66%.

Table 21. Hot-Line cost of downtime.

Level of Overall Hot-Line Downtime	Hours of Hot-Line[1] Production Lost Annually	Annual Cost[2] of Lost Hours	Annual[3] Marginal Savings
50%	4,160	$790,000	--
45%	3,740	710,000	$80,000
40%	3,325	630,000	80,000
36%	2,995	566,000	64,000
34.66%	2,880	547,000	19,000
30%	2,490	475,000	62,000
25%	2,080	395,000	80,000
20%	1,662	315,000	80,000
15%	1,248	235,000	80,000

[1] This is 8,320 hours/yr. available for Hot-Line production times the level of overall downtime.

[2] This is $190/hr. of Hot-Line Downtime times the Hours of Hot-Line Production Lost Annually.

[3] This is the savings available by reducing Hot-Line Downtime from the preceding level to the level listed. That is, going from 50% Hot-Line Downtime to 45% would save $80,000 per year.

Cost of Hot-Line Lost Sales

The relationship between Hot-Line breakdowns and Hot-Line Lost Sales is the next area examined. The reader will recall that plant personnel estimate 24 hours of breakdowns must occur within a five-day period to cause a Hot-Line Lost Sale.

The five-day period is the fastest processing time through Remelt. If the ingots can be imagined as going through a queue to get to the Hot-Line, each delay at the Hot-Line slows the entire queue down. If the entire queue is "set back" 24 hours, then the customer will cancel his order. The probability that any ingot which has just started Remelt processing will be "set back" by 24 hours by the time it reaches the Hot-Line must be determined.

Mann's (8) probability distribution for the probability of X breakdowns in time t is used, with X the number of breakdowns causing 24 hours downtime and t as five days.

$$P\ X, t = \frac{Z^X e^{-Z}}{X!}$$

where:

Z = the mean number of Hot-Line failures in a five-day period, and

X = the number of Hot-Line failures which would cause a total amount of breakdown of 24 hours.

Z is found to be equal to .67 breakdowns per hour:

8,320	Hours available annually for Hot-Line production,
- 1,611	The amount of Hot-Line production time consumed by Operational and Out=of metal Delays at the Hot-Line[14] equals
6,709	Hours per year in which breakdowns can occur.

There are 4,470 Hot-Line breakdowns per year,[15] each averaging .309 hr. duration. Z, the mean number of breakdowns per hour is therefore .67 breakdowns/hr.:

$$\frac{4,470 \text{ breakdowns/yr.}}{6,709 \text{ hrs./yr. available for breakdowns}} = .67 \frac{\text{breakdowns}}{\text{hour}}$$

X, the number of breakdowns which would cause a delay of more than 24 hours in a five-day period is simply 77.8.

$$\frac{24 \text{ hrs.}}{.309 \text{ hrs./breakdown}} = 77.8 \text{ breakdowns}$$

This frequency can be reduced to a frequency per hour figure:

$$X = 77.8 \text{ breakdowns/five-day period} = \frac{77.8}{120 \text{ hrs.}} = \frac{.648 \text{ breakdowns}}{\text{hour}}$$

The probability of Hot-Line breakdowns causing Hot-Line Lost Sales is approximately .58[16]:

$$P, 65, 100 \text{ hrs.} = \frac{67^{65} e^{-67}}{65!} = .58$$

[14] 8,320 hrs./yr. x 19.4% (the Hot-Line operational and out-of-metal delay level in 1970).

[15] From earlier computations in this study.

[16] From CRC Standard Mathematical Tables (2, p. 461). For ease of computation, X was used as 6.5, Z as 6.7. X and Z are shown as whole numbers on a 100 hr. basis for mathematical correctness.

This result would seem to indicate that approximately 58% of the annual Hot-Line output incurs a Lost Sale. This is definitely not the case! The reason for this erroneous figure is the fact that not all of Kaiser's business is on a custom order basis. Much of their production does not have a severe lead time requirement and orders which do have a strict lead time requirement are probably processed through Remelt even faster than the five-day figure used to compute the probability of Lost Sales at the Hot-Line.

Plant personnel estimate that only 1,000 ingots suffer a Lost Sale each year at the Hot-Line. This figure of 1,000 ingots per year corresponds to a very low probability of breakdowns. Since the average breakdown frequency of .67 breakdowns per hour is constant, the only parameter that can change in the Poisson probability calculation is the time period in which the breakdowns must occur to cause a Lost Sale. 1,000 Lost Sale ingots per year corresponds to a pre-empted Remelt processing time of only 47.7 hours. This figure is assumed to be correct since ingots are stored after Scalper processing in the same fashion that multi-purpose ingots are stored in the Cold Mills. As a result, Scalper ingots can replace delayed ingots to prevent Lost Sales.

If 47.7 hours is used as the Remelt processing time, it is interesting to calculate the effect that repairing all Eight Typicals would have on Hot-Line Lost Sales. A reduction of the level of Hot-Line breakdowns from 36% to 34.66% would change the frequency of

Hot-Line breakdowns in a one-hour period from . 67 to . 613:

8,320 hrs/yr. available for Hot-Line Production

x15.26% New Hot-Line Downtime level
1,270 hrs/yr. consumed by Hot-Line Downtime

$$\frac{1,270 \text{ hrs/yr.}}{.309 \text{ hrs/breakdown}} = 4,120 \text{ breakdowns/yr.}$$

$$\frac{4,120 \text{ breakdowns/yr.}}{6,709 \text{ hrs/yr. available for breakdowns}} = .613 \text{ breakdowns/hr.}$$

At 47.7 hours pre-empted Remelt processing time the new number of breakdowns per hour required to cause a Hot-Line Lost Sale is 1.63:

$$X = \frac{77.8 \text{ breakdowns/hr.}}{47.7 \text{ hr. period}} = 1.63 \text{ breakdowns/hr.}$$

The probability of Hot-Line Lost Sales occurring at the 34.66% Hot-Line breakdown level is then .00048:

$$P, 163, 100 \text{ hrs.} = \frac{61^{163} e^{-61}}{163!} = .00048$$

At this probability level only 37 ingots per year would incur a lost sale at the Hot-Line due to breakdowns:

.00048 x 77,200 ingots/yr. = 37.05.

The new annual lost sale cost would then be $11,100:

37 ingots x $300/lost sale = $11,100.

The reduction of Lost Sales by repairing the Eight Typicals would result in a savings of $288,900:

$300, 000 (the lost sale cost at 1, 000 ingots/yr.),

- $ 11, 100 (the new lost sale cost at 37 ingots/yr.),

= $288, 900 the annual savings by repair of the Eight Typicals.

These annual savings are based on the assumption that all the estimates used in calculating the probabilities are correct. It is doubtful whether this is a valid assumption, however, and it would seem far wiser to simply store more ingots at the Scalpers than to repair the Eight Typicals at a cost of $2, 332, 500. Storing an additional inventory of 83 ingots would achieve the same effect of preventing Lost Sales and only cost $6, 600 per year:

$$\frac{1,000 \text{ ingots/yr.}}{12 \text{ mo./yr.}} = 83 \text{ additional ingots in Remelt inventory, and}$$

83 more ingots x $6. 75/mo. x 12 mo. /yr. = $6, 600.

By repairing the Eight Typicals this inventory cost could be saved and as a result, the cost of additional inventory to prevent Lost Sales at the Hot-Line is claimed as the Hot-Line Cost of Lost Sales savings available.

Summary of Hot-Line Costs

A summary of the money that could be saved at the Hot-Line by repairing the Eight Typicals are shown in Table 22.

Table 22. Summary of possible Hot-Line savings.

Category of Savings	Annual Savings
Hot-Line Downtime	$19,000
Hot-Line Lost Sales	$ 6,600

CHAPTER VI. EVALUATION

Comparison of Costs Which can be Saved by Repair of the Eight Typicals on the Single-Channel

For ease of comparison, the summaries of possible savings shown in Chapter V, Tables 21 and 22, are presented below in Table 23. Also shown in Table 23 is the annual cost of breakdowns for the Eight Typicals. This figure is simply the cost per occurrence from Table 14 times the yearly frequency of Table 13.

Table 23. Savings possible by repair of the Eight Typicals.

Area	Type of Savings	Annual Savings[1]
Hot-Line	Downtime	$19,000
	Lost Sales	6,000
	Temporary Breakdown Repair	133,250
Cold Mills	Downtime (Worst Case)	9,192
	Inventory	12,798
	TOTAL	$180,840

[1] The annual savings available by repairing the Eight Typicals are the costs which can be avoided.

As mentioned previously, the major maintenance decision is currently based on the cost of temporary breakdown repair and the cost of Single-Channel downtime. These two costs account for approximately 84.4% of the savings shown above:

$133,250 + $19,000 = $152,250

$$\frac{\$152,250}{\$180,840} = 84.4\%.$$

Since so many of the other savings are very "iffy," it is probably safe to assume that consideration of the cost of temporary repair and the cost of Single-Channel downtime are the most important inputs to the major maintenance decision. This means that Kaiser personnel have been analyzing their major maintenance decisions correctly, even though it was done by the "seat of their pants." While the results of this study will probably not change decision making policies at Kaiser, it should provide very effective tension release for those personnel responsible for major maintenance decisions. It should be emphasized, however, that ignoring costs other than temporary repair and downtime is only advisable while Remelt and Cold Mill in-process inventories are maintained.

Use of Inventory as a Lost Sale Deterrent

As seen in the Lost Sale sections of Chapter V, a large number of ingots would suffer Lost Sales were it not for the presence of in-process inventory. Even with the Eight Typicals repaired, the Hot-Line would suffer a 49.5% Lost Sale level since without Scalper inventory, the processing time at Remelt would be five days, not 47.7 hours. The number of breakdowns per hour required to cause a lost sale would thus be .648. Therefore, the probability of Hot-Line breakdowns causing lost sales would be .495:

$$P_{.648,1} = \frac{.61^{.648} e^{-.61}}{.648!} = .495$$

At the Hot-Line production level possible with the repair of the Eight Typicals, 77,200 ingots could be manufactured annually. Therefore, even if the Eight Typicals were repaired, 49.5% of these ingots would incur a Cost of Lost Sales and $11,450,000 would be lost annually:

77,200 ingots/yr. x .495 x $300/ingot = $11,450,000.

The Cold Mills would also suffer a high incidence of Lost Sales were no in-process inventory stored there, even with the Eight Typicals repaired. Lost Sale cost was $3,730,000 in the Cold Mills with no in-process inventory.[17] If the Eight Typicals were repaired, 1,418 less ingots would suffer lost sales in the Cold Mills,[18] thus saving $412,602 per year in Cold Mill Lost Sales. Even with this savings $3,317,398 would be lost annually:

$3,730,000 - $412,602 = $3,317,398.

These astronomical costs of losing sales are expounded under the assumption of no in-process inventory. They show that even by repairing the Eight Typicals, a large amount of money would be lost if no in-process inventory were stored. Even with all the breakdowns

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[17]As seen in the Cost of Cold Mill Lost Sales section of Chapter V.

[18]Same section and chapter.

eliminated on the Hot-Line, many sales would be lost without an in-process inventory since many Hot-Line delays are caused by operator errors and lack of metal to process.

The possible effects of eliminating in-process inventories are presented as a reinforcement of the established policy at Kaiser of maintaining in-process inventories.

CHAPTER VII. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Assumptions Made in the Study

This examination of the n-one-n production configuration at Kaiser was based on several key assumptions. Without accurate data concerning the frequency and duration of breakdowns, it was assumed that an average breakdown on the Hot-Line would leave it idle for .309 hours and that the Hot-Line suffer 4,470 of these breakdowns per year. These figures are obviously debatable but they are based on estimates by men in the field of maintenance and are as accurate as possible without an expensive data retrieval system.

The lost sale costs hypothesized in the study are developed using the average breakdown duration and frequency estimates. The lost sale costs are also based on estimates concerning the processing time of the Cold Mills and Remelt and the delay necessary to cause Lost Sales there. Again, without an expensive study, more accurate data was not obtainable and the estimates were taken in good faith.

Data used to compute costs other than Lost Sales are felt to be quite accurate. While the average frequency and duration of breakdowns is not recorded by the maintenance department, the costs of temporary and permanent repair are. The cost of Hot-Line Downtime is also quite accurate since the cost per hour of downtime and the number of hours of downtime are already tabulated by Kaiser.

Key Results of the Calculations

The significant result of this study for Kaiser is that, at the current level of Hot-Line Delays (36%) permanent repair of Hot-Line equipment should be based on: (1) the Cost of Hot-Line Downtime, and (2) the Cost of Breakdown Repair. Not only do these two costs comprise 84.4% of the total savings available due to permanent repair, they are also the firmest mathematically. As seen in the "Assumptions Made" section above, the Cost of Hot-Line Downtime and the Cost of Breakdown repair are based on very accurate data while the other 15.6% of the savings are based on weak assumptions.

The second result of this study which is of interest to Kaiser concerns their in-process inventory. At the current level of 36% Hot-Line Delay, in-process inventory is a cheaper deterrent to lost sales and downstream downtime than a massive program of permanent repair of the Hot-Line breakdowns.

General Results of the Study

The importance of costs other than temporary repair and single-channel downtime are directly related to the over-all level of single-channel delay. As seen in the simulation results, a great deal of money could be saved by permanent repair of the Eight Typicals were the Hot-Line operating at a 50% over-all delay level rather than the current level of 36%. It is interesting that this is so, as costs are usually considered in terms of absolutes. While this may be unclear, a simple example illustrates the relationship between the level of downtime and the relative importance of the costs. A few flat tires can always be expected as concomitant to the ownership of an automobile. While a low frequency of flat tires has little more consequence than personal inconvenience, the situation would change if a person suffered four flat tires per week. Repeated tardiness in getting to work may threaten one's occupation and then the economic importance of permanently curing the flat tire problem would be magnified, even though the cost of temporarily repairing the flat had not changed.

Other facilities would have costs of operation different from Kaiser's and this is obviously an important consideration in attempting to generalize. While two costs comprised 84.4% of the savings from permanent repair at Kaiser, this figure would probably not be the case elsewhere. For example, inventory was found to be a cheaper lost sale deterrent than single-channel permanent repair, but aluminum does not require refrigeration; a cold storage requirement at a food processing plant could radically alter the relationship between costs of repair and inventory storage.

The obvious conclusion, therefore, is that a study similar to this one would have to be conducted at a different facility with different operating parameters, but the same analysis procedures and format could be followed.

Recommendations

Hot-Line Lost Sales Requires Further Study

The fact that Lost Sales can occur at the Hot-Line due to Hot-Line breakdowns requires further study. The potential of 1,000 ingots incurring a Lost Sale at the Hot-Line and $300,000 being lost annually as a result should indicate that the situation is such that savings are available in this area. As shown in the Cost of Hot-Line Lost Sales portion of Chapter V, the $300,000 lost annually to Hot-Line lost sales could possibly be avoided by increasing the average Scalper inventory by 83 ingots at a cost of $6,600 per year.

Such dramatic savings available deserve further study but this is beyond the scope of this work.

Better Data Needed

Further study of the savings available at the Hot-Line by increasing the Scalper inventory requires better data on the time delay necessary to cause a Lost Sale. The pre-empted processing time through Remelt is so crucial that a speedup of only a few hours could possibly achieve the same effect that increasing Scalper inventory would have.

Market Survey of the Cause of Lost Sales

This work was performed under the assumption that the 1,000 ingots which suffer Hot-Line lost sales are caused by delays. It is quite possible that other factors cause the cancellation of orders and a study of the correlation between production delays and order cancellations should first be made to verify the viability of increasing the Scalper inventory.

Development of a Decision Algorithm for Single-Channel Breakdown Repair

As seen in Chapter VI the most important inputs to the major maintenance decision are the cost of single-channel downtime and the cost of temporary repair. This conclusion is felt to be relevant so long as a policy of maintaining in-process inventories is followed. To improve the major maintenance decision making process, a decision algorithm is needed.

Description of Algorithm

A procedure is required to determine the probability that a piece of equipment which has just begun breaking down will continue doing so.

Such a decision algorithm would allow a maintenance manager to catch a chronically defective piece of equipment by "nipping it in the bud," rather than looking back at the frequency of breakdowns during the last six months and saying, "Gosh, we should have repaired that earlier."

Data Required

Development of such an algorithm would require accurate recording of the cause and nature of every Hot-Line breakdown. Such records could then be formed into a frequency distribution from which alpha and beta risks[19] could be computed for repairing or not repairing a chronically defective piece of equipment. Use of the frequency distribution would allow projection of the probability of future breakdowns given the previous history of a "new" breakdown.

Development of the records needed would not require the elaborate type of computer data retrieval system mentioned in Chapter II. A system of this sort is therefore not recommended for Kaiser's

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[19]An alpha risk would be the probability of not permanently repairing a piece of equipment when it needs permanent repair, while a beta risk is the probability of permanently repairing a piece of equipment which should not have been so repaired. Analyses using the two opposing types of risks are associated with quality control where a sampling plan is developed to avoid extensive penalty from incurring either alpha or beta costs. For further information see Duncan (4, p. 154).

use as manual record keeping would be adequate. It should be mentioned, however, that data besides the type used in this study might be of interest to Kaiser and a computerized data retrieval system would then be useful.

Work orders are currently made out for each Hot-Line breakdown and it would just require manual effort to condense these work orders into a usable format. Doing this is obviously beyond the scope of this thesis and it is hoped that such development of a frequency distribution may also be done at Kaiser.

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APPENDICES

APPENDIX A: SUMMARY OF SAVINGS AVAILABLE BY A REDUCTION OF HOT-LINE DOWNTIME

As seen in the main body of this text, in-process inventory must be retained to prevent Lost Sales. The savings that are available by reducing Hot-Line downtime are therefore confined to the areas of Cost of Hot-Line Downtime and Cost of Cold Mill Downtime. These are presented below.

The table shows the savings that are available by going from the previous level of downtime to the one opposite the savings listed. For example, going from 50% Hot-Line Downtime to 45% would save $80, 000 per year in Cost of Hot-Line Downtime and the savings are read across from the 45% Hot-Line Delay level.

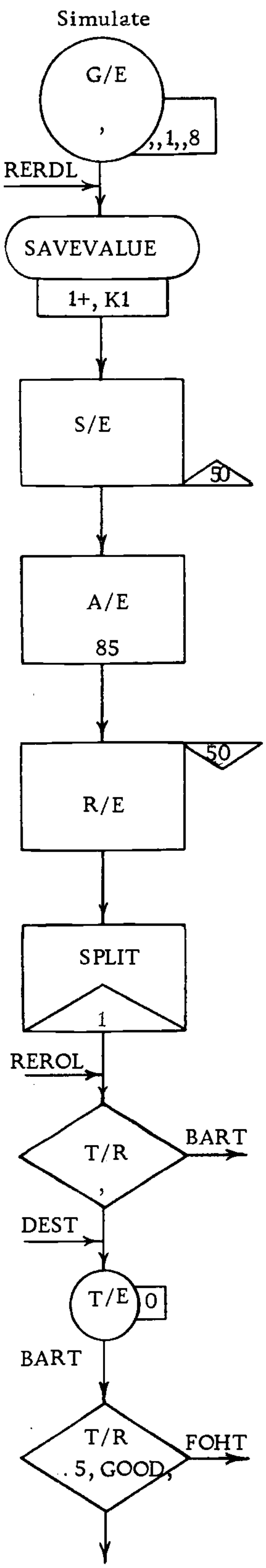
Best Case and Worst Case savings are also presented which correspond to the definitions in the main body of the text. The reader is reminded that these savings are only available when the Hot-Line is on a Twenty Shift schedule, as well as the Slitters and Five-Stand, while the Four-Highs savings are based on a 15-shift schedule there.

Hot-Line		Five-Stand		Four-Highs		Slitters	
Downtime Level	Hot-Line	Best	Worst	Best	Worst	Best	Worst
50%							
45%	$80	$61.5	$154.9	$3.80	$23.0	$23.95	$43.60
40%	"	$28.5	$48.5	$5.80	$35.5	$ 5.66	$10.35
35%	"	none	none	$4.35	$26.5	$ 4.21	$ 7.70
30%	"	"	"	$9.63	$58.3	$ 2.86	$ 5.15
25%	"	"	"	$1.52	$ 9.2	$ 1.42	$ 2.61
20%	"	"	"	$8.12	$49.7	$ 2.81	$ 5.17
15%	"	"	"	$3.38	$20.3	$ 1.42	$ 2.57

APPENDIX B. SIMULATION PROGRAM

```
       SIMULATE
       GENERATE    ,,,1,,8
 REROL SAVEVALUE   1+,K1
       SEIZE       50
       ADVANCE     85
       RELEASE     50
       SPLIT       1,REROL,,8
       TRANSFER    ,BART
  DEST TERMINATE   0
 BART  TRANSFER    .5,GOOD,FOHI
 GOOD  TRANSFER    .2,FIVE,CUTT
*THIS IS THE FIVE STAND PORTION OF THE MILL
 FIVE  MARK        2
       QUEUE       1
       SEIZE       1
       DEPART      1
       ADVANCE     199,19
       RELEASE     1
       SAVEVALUE   2+,K1
  SORT TRANSFER    .75,DEST,CUTT
*THIS IS THE FOUR HIGH PORTION OF THE MILL
 FOHI  MARK        3
       QUEUE       2
       ENTER       1
       DEPART      2
       ADVANCE     152,15
       LEAVE       1
       SAVEVALUE   3+,K1
*THIS IS THE SLITTER PORTION OF THE MILL
 CUTT  MARK        4
       QUEUE       3
       ENTER       2
       DEPART      3
       ADVANCE     430,43
       LEAVE       2
       SAVEVALUE   4+,K1
       TRANSFER    ,DEST
       GENERATE    1200,,,1
       ADVANCE     18000
       PRINT       ,,X
       TERMINATE   1
 1     STORAGE     3
   2   STORAGE     5
       START       1
       END
```

APPENDIX C. GPSS FLOW CHART



Generate the first Ingot. Limit Parameter to 8.

Record total number of ingots produced.

Hot-Line Production, Ingots loaded

Ingot Processed.

Ingot unloaded.

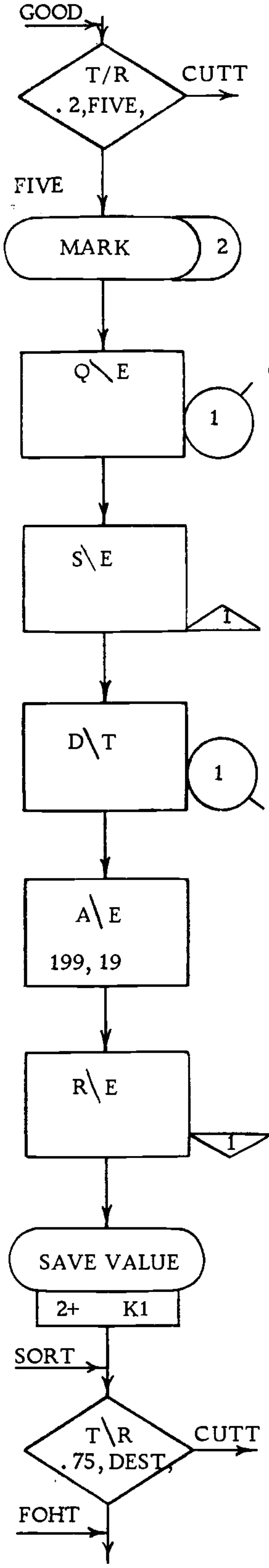
Parent goes to Cold Mill inventory, Offspring goes to be "new ingot."

All ingots routed to Cold Mill Area.

Transactions are Destroyed.

These transfer blocks sort the Hot-Line output to achieve the proper mix. FOHI is the Four-Highs.

Go to top of next column.



Cutt is the Slitters, Five is the Five-Stand.

This is the beginning of the Five-Stand, the time that the ingots enter the inventory is recorded.

Queue 1 is the inventory.

The ingot is loaded on the Five-Stand.

Ingot leaves inventory.

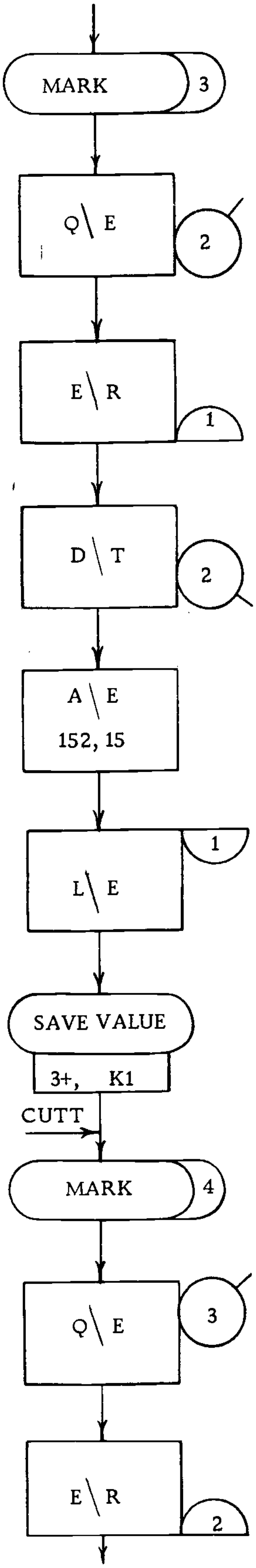
Five-Stand processes ingot.

The ingot is unloaded.

Five-Stand Production is recorded.

Five-Stand production is sorted, 75% of the output going to the slitters, 25% to other areas not modeled.

Go to top of next column, next page.



This is the beginning of the Four-Highs.

The Four-High inventory.

Ingots are loaded on the Four-Highs.

Ingots are marked as leaving the inventory.

The Four-Highs process the ingots.

The ingots are unloaded.

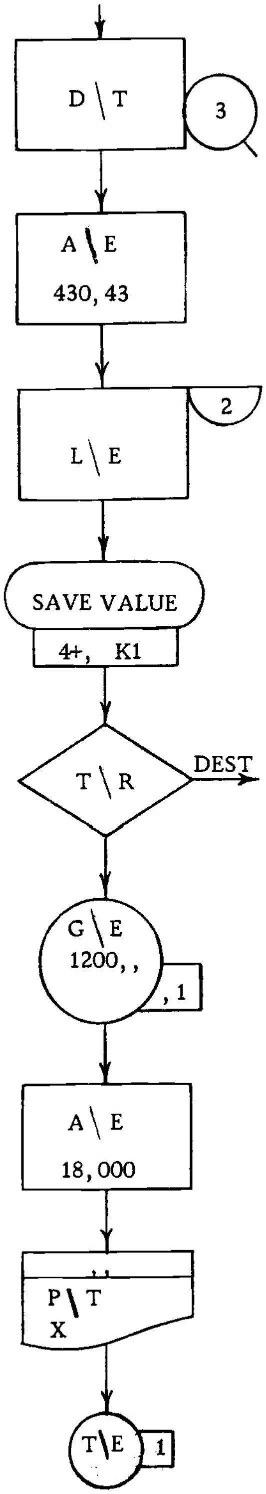
Record the number of ingots produced at the Four-Highs.

This is the beginning of the Slitters. The time that ingots enter is recorded.

The Slitter Inventory

Ingots are loaded on the Slitters.

Go to top of next column.



Ingots are marked as leaving the inventory.

The Slitters process the ingots.

The ingots are unloaded.

Record the number of ingots produced at the Slitters.

Send ingots to other areas not modeled.

Create a clock to end the run in 1/28 month.

Complete 1/20 time duration.

The final values of all the Save values are printed.

The run is terminated.

1	STORAGE	3
2	STORAGE	5
3	START	1
	END	

APPENDIX D. AVERAGE COLD MILL INVENTORY LEVEL

Cold Mill	Monthly Inventory					
Process Center	Feb.	Mar.	April	May	June	July
Five-Stand	98	116	273	138	128	153
Four-Highs	998	1,168	783	768	935	652
Slitters	398	349	546	318	304	406
TOTAL	1,494	1,633	1,602	1,224	1,367	1,211

Total for six months = 8,531 ingots

Average in-process inventory = $\frac{\text{8,530 ingots}}{\text{6 mo.}}$ = 1,424 ingots