APPLICATION OF PLANNED - REPLACEMENT POLICY IN A COPPER-WIRE DRAWING COMPANY

by

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We hereby recommend that the thesis entitled "Application of Planned-Replacement Policy in a Copper-Wire Drawing Company" submitted by Ömer Kudret Tan be accepted in partial fulfillment of the requirements for the Degree of Master of Science in Industrial Engineering, School of Engineering, Boğaziçi University.

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Ö.Kudret Tan

January 28, 1982

ABSTRACT

This thesis deals with the establishment of a planned-replacement system in the wire drawing department of Rabak Electrolytic Copper and Products Co., for the achievement of operational cost savings, through reduction of the annual maintenance costs. The major inputs utilized by the model are, the component failure data, planned and failure replacement costs for the critical components of the wire drawing machinery. The model is also expressed under constraint setting by imposition of minimum production tonnage, maximum production-losses allowed and maximum maintenance cash budget constraints. The major outputs of the model are, the optimal planned replacement periods, for the analysed components, which minimize the annual expected planned-replacement policy costs. The application of the proposed model will also lead to more reliable production scheduling, while decreasing expected machine-breakdowns and production losses in the drawing department. In the overall, the model will improve, the wire drawing operations, while bringing a systematic approach to the solution of the currently existing maintenance problems. The application of the proposed model is possible in other industries as textile, paper, aluminium and iron wire drawing etc. where continous production is vital for the quality and costs of the operations. The extensions to the work can be made in spare parts safety stock planning and in optimal maintenance work and personnel scheduling etc.

ÖZET

Bu tezde, Rabak Elektrolitik Bakır ve Mamulleri A.Ş. Kağıthane Fabrikasında yer alan tel çekme bölümünde, plânlı değiştirme sisteminin oluşturulması ile, yıllık bakım giderlerinin enküçüklenmesi amaçlanmıştır. Önerilen modelin girdileri, kritik makina parçalarına ilişkin bozulma kayıtları ile planlı ve bozulma sonucu parça yenileme veya değiştirme giderleridir. Model, enaz üretim tonajları ve ençok üretim kayıpları ile ençok bakım nakit bütçe kısıtları altında da genelleştirilmektedir. Modelin çıktılarını, yıllık plânlı-bakım politikası giderlerini enazlayan, enuygun plânlı-değiştirme süreleri oluşturmaktadır. Önerilen uygulama aynı zamanda tel çekme bölümünde daha güvenilir bir üretim planlanmasını mümkün kılarken, beklenen makina duruşlarını ve üretim kayıplarını büyük oranda azaltacaktır. Genel olarak, sözkonusu üretim bölümündeki faaliyetlerin daha güvenilir ve verimli olması sağlanırken, mevcut bakım problemlerinin çözümüne daha sistematik bir yaklaşım getirilmiş olmaktadır. Önerilen modelin, sürekli üretimin kalite ve giderler açısından büyük önem taşıdığı tekstil, kağıt, alüminyum, çelik tel vs. gibi endüstri kollarında da uygulanması mümkün bulunmaktadır. Modele eklemeler, parça emniyet stoku planlanması, enuygun bakım personeli ve bakım aktivitesi planlanması konularında yapılabilir.

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I. INTRODUCTION

I.1. OBJECTIVES AND PRELIMINARIES

This study focusses on the development of a maintenance system in a copper-wire drawing plant. The primary objective is to determine effective planned replacement times for the critical components of wire drawing machinery. Thus, it is sought to increase the operational profits through reduction of probable failures and lost production.

In many wire-drawing firms, continous production is very vital once the line is set up for the appropriate wire diameters. The reason is that, both the quality and the operational costs of drawn wire are closely related to continous production. Lost production costs due to machine breakdowns are notably high. When unexpected failures occur, the management needs to give rush-orders of spare parts, which in turn significantly increases the costs of component replacement.

The currently applied repair or replace-on-failure policy, costs the company approximately 348 million TL. per year, taking into account the costs of lost-production,material and labour. The gross profits of the company in the year this analysis is carried, amounts to 450 million TL.'s. It is apparent that the current maintenance policy costs constitutes approximately 77 % of the gross-profits of the company and deserves attention for analysis. The application of the proposed planned replacement policy will maintain a cost advantage of about 86.5 million TL.'s annually to the company under study. It will also provide a systematic approach to the maintenance problems in the drawing department, by periodic replacement of the critical components of the drawing machinery. Also, significant productivity increases will be realized due to decreased downtimes, along with quality improvements in drawn wires, because of less welding requirements, less scrap and more homogenity on wire surfaces. The implementation of the proposed policy will also enable more reliable production scheduling in the company.

This study can be generalized to other wire-drawing operations, such as iron, steel, brass, aluminium wire-drawing and can easily be adapted to other firms.

Before reviewing some fundamental replacement models, the basic terminology, symbols and lifetime distributions will be introduced. If we consider a machine in any production shop, a realization of its status through the time horizon is illustrated in Figure 1.1. The term machine availability is used to describe the probability that the machine can operate under satisfactory conditions. The operating time stands for the periods when machine is actually working. The remaining portion of the available time is referred to as idle time. The downtime consists of three phases. The first phase includes administrative and logistic work such as informing the maintenance department, procurement of spare parts, forming the repair team and scheduling the repair or replacement activity. This is followed by an active repair time and a period of some more administrative work.

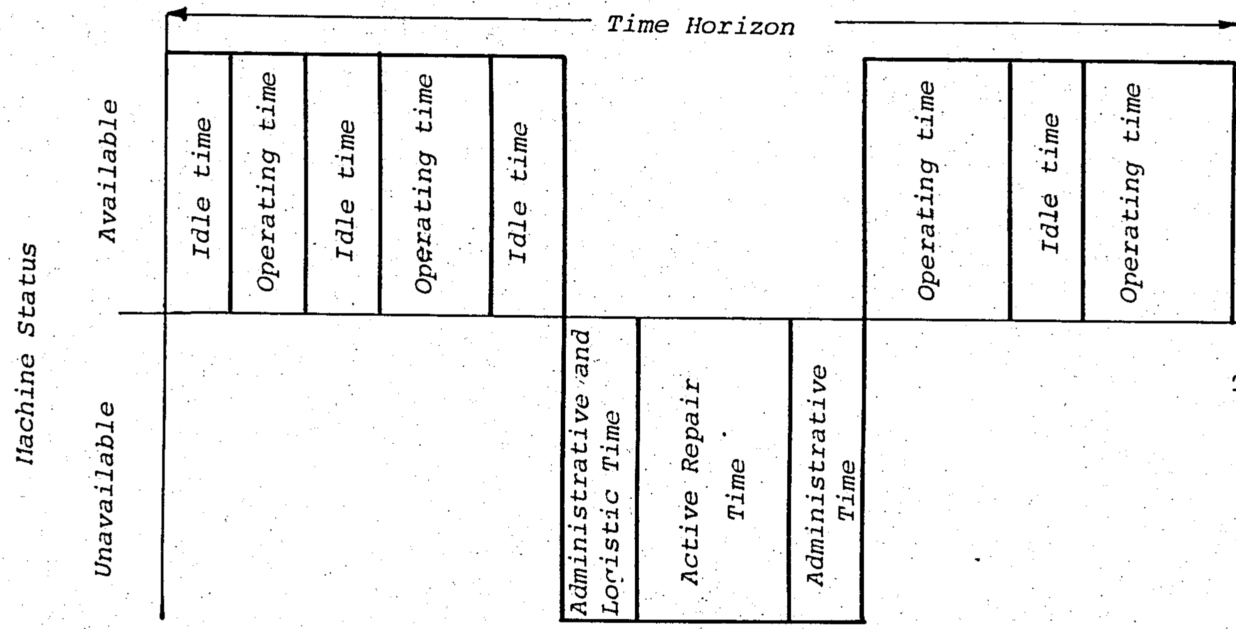

FIGURE 1.1 MACHINE STATUS OVER A TIME HORIZON

Let f(t), F(t) and R(t) stand for the probability density function (pdf), cumulative distribution function (cdf) and the reliability function respectively for the lifetime models. The hazard rate (also called failure rate) is the instantenous probability of failure at time t given that the unit has survived upto that time point. This is given as

$$r(t) = f(t)/R(t)$$

The major lifetime distribution to be employed in this study is Weibull distribution. This is because Weibull distribution can adequately represent most of the failure data collected.

The Weibull model which is frequently utilized for wear-out types of failures is initially developed by Weibull in 1951. The probability density function can be expressed as;

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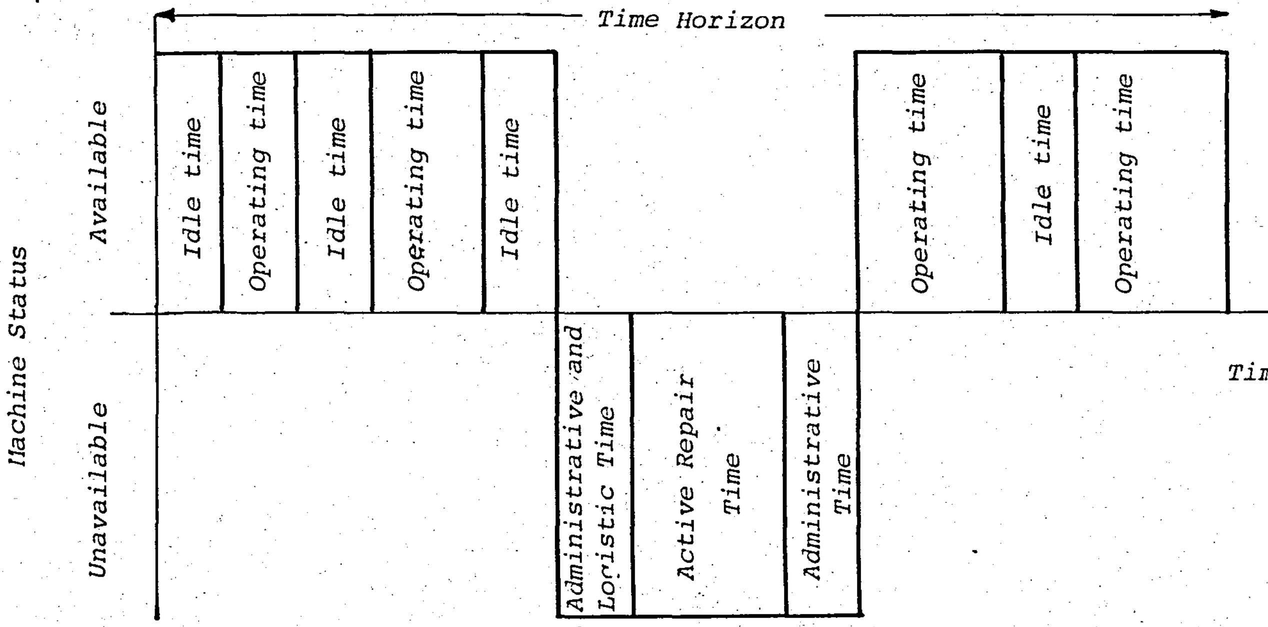

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$$f(t) = \frac{\beta}{\lambda}\left(\frac{t}{\lambda}\right)^{\beta-1} \cdot \exp\left[-\left(\frac{t}{\lambda}\right)^{\beta}\right]$$

where its hazard rate is;

$$r(t) = \frac{\beta}{\lambda}\left(\frac{t}{\lambda}\right)^{\beta-1} \qquad \text{with } \beta > 0 \text{ and } \lambda > 0$$

and its reliability function is;

$$R(t) = e^{-(t/\lambda)^{\beta}}$$

The parameters λ and β are referred to as scale and shape parameters respectively. The scale parameter is a measure of degree of spread, whereas the shape parameter indicates the degree of skewness of the p.d.f.

When $\beta=1$, exponential lifetime model emerges as a special case of Weibull. Exponential distribution yields a constant hazard rate. When $\beta<1$, this means that hazard rate is of monotonically decreasing type. When $\beta>1$, the hazard rate is monotically increasing. The failure rate function is exemplified in Figure 1.2.

The planned-replacement times need to be obtained only for the case $\beta>1$. Otherwise, the policy of replace on failure is optimal.

When $\beta\geq 4$, the skewness of the Weibull distribution starts to disappear and it tends to look more like a symmetric distribution.

Log-Normal failure probability distribution is also applicable for wear-out failures due to its increasing failure rate. The p.d.f. of this distribution is expressed as;

$$f(t) = \{ \frac{1}{\sqrt{2\pi}\,\sigma . t} e^{\left(\frac{-[\ln t-\mu]^2}{2\sigma^2}\right)} \}$$

where $\sigma>0$.

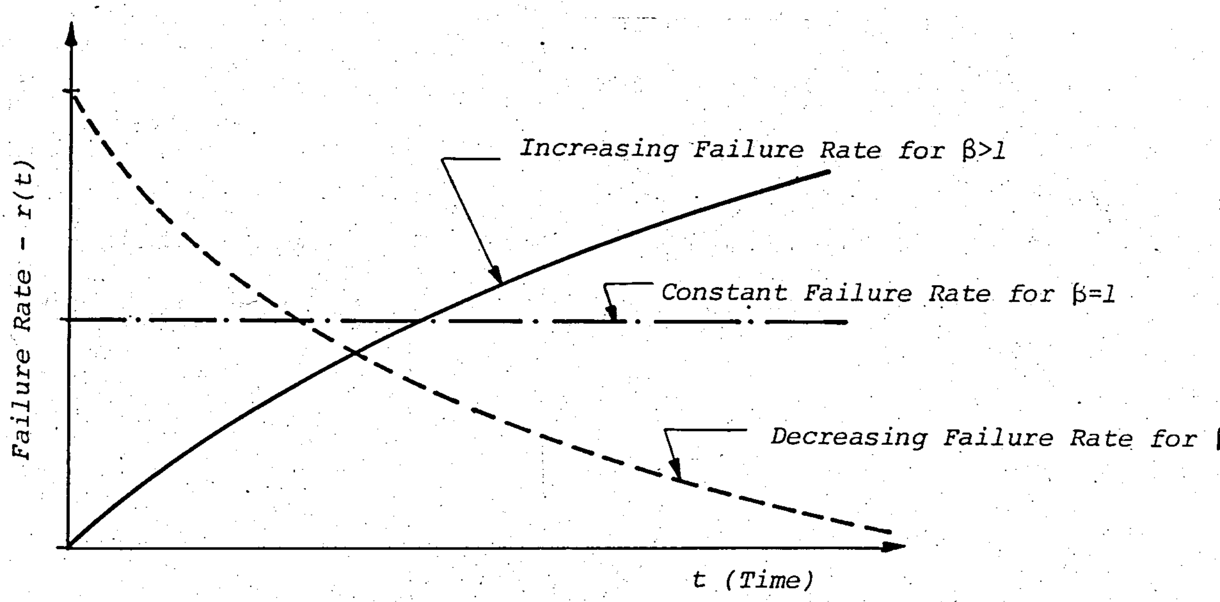


FIGURE 1.2 WEIBULL FAILURE RATE FUNCTION

I.2. LITERATURE SURVEY ON PLANNED REPLACEMENT POLICIES

In preventive replacement strategies, a unit is replaced either at some specified time or at time of failure, whichever occurs first. Such policies are meaningful for the maintenance systems, because the replacement cost incurred at failure is usually much higher compared to the planned replacement cost. Also, the operating items have the aging characteristics. In other words, the failure rate r(t) is IFR (Increasing Failure Rate) type and items tend to wear out as their operational time increases{Barlow and Proschan, 1962}.

For a planning horizon t, the expected total replacement cost $E[TC]$ can be expressed as:

$$E[TC(t)] = C_p E[N_p(t)] + C_f E[N_f(t)]$$

where:

C_p = Planned-replacement cost

C_f = Replacement cost on failure

$N_p(t)$ = Number of planned replacements in period (0,t)

$N_f(t)$ = Number of failures in period (0,t)

The objective can be stated as the minimization of the expected cost per unit time, $E[C]$ for an infinite time horizon{Ross, 1970}.

$$E[C] = \lim_{t \to \infty} \frac{E[TC(t)]}{t}$$

It can be shown{Jardine, 1978} that the expected cost per unit time is equal to:

$$E[C] = E[Y]/E[Z]$$

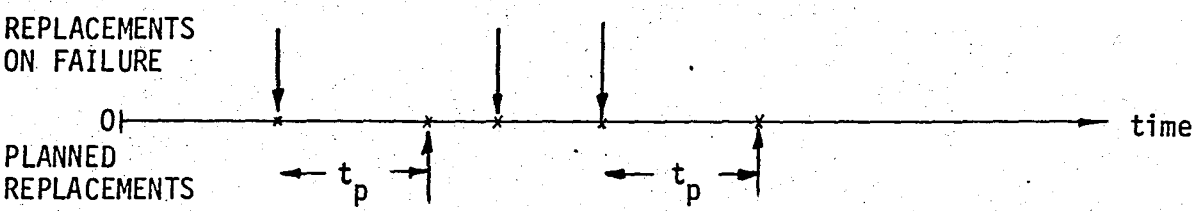
where:

Y = Cost incurred between two renewals

Z = Cycle time(duration of renewal period).

We shall refer to those time points at which the process starts over again, as renewal times. In the remainder of this section, some of the major preventive replacement policies will be reviewed.

Age Replacement Policy (ARP): An item is either replaced at a specified age t_p or on failure. For a planning horizon t, a realization of renewal times is portrayed in Figure 1.3. Each crossmark corresponds to a renewal point in this figure.



GURE 1.3 A REALIZATION OF REP. TIMES FOR A PLAN. HORIZON t FOR AGE REP. POLICY

The value of t_p can be found by minimizing the expected cost per unit time:

$$E[C] = \frac{c_f[1-R(t_p)] + c_p R(t_p)}{t_p R(t_p) + M(t_p)[1 - R(t_p)]}$$

where $M(t_p)$ is the mean time to failure (MTTF), of the unit given that planned replacement occurs at age t_p.

Block Replacement Policy (BRP): In these policies, planned replacements occur at fixed intervals of length t_p. Thus, they are also referred to as constant interval policies. A realization of replacement times and renewal times is illustrated in Figure 1.4. It should be noted that the renewal times designated with crossmarks appear only at fixed intervals t_p.

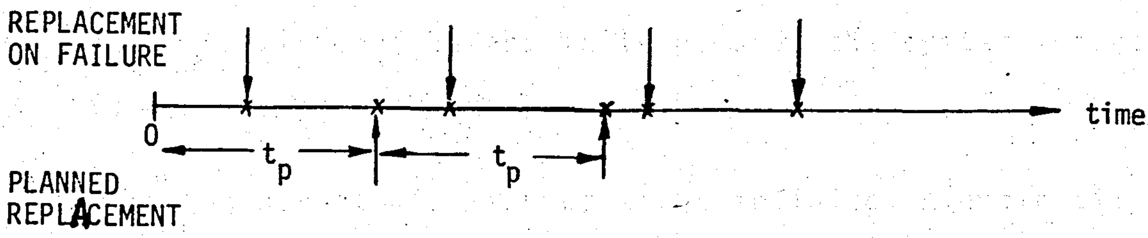


FIGURE 1.4 A REALIZATION OF REPLACEMENT TIMES FOR A PLANNING HORIZON t FOR A BLOCK REPLACEMENT POLICY.

The value of t_p can be found by minimizing:

$$E[C] = \frac{c_f E[N_f(t_p)] + c_p}{t_p}$$

Delivery and Replacement Policy With Delay: In this type of policy, a delay period as the delivery period, is introduced into the system. This period is viewed as extending the expected stage duration. For instance, we could consider the following application given by T.Nakagawa{Nakagawa, 1977}.

A one unit system is given with failure time distribution F(t). The inventory of spare unit is assumed to be at most one unit. The unit starts operating and the spare unit is ordered at t=0. The delivery of the spare unit will be at $t=t_o$ (called the planned delivery time of spare unit). The spare unit cannot fail, its installation time is close to zero and replacement of it starts the next renewal period.

The spare unit's ordering cost is c_o, which includes its own cost also.

If the unit fails before spare unit is delivered, the system incurs a unit cost k for idle time due to late delivery.

If the unit is delivered before it is needed, the system incurs a unit cost c_i for inventory.

The planning horizon is assumed to be infinite. A cycle time or a renewal period is identified here as the period starting just after its replacement. The expected cost of one stage is given then, by sum of ordering, downtime and inventory costs:

$$c_0 + k.\int_0^{t_0} (t_0-t)dF(t) + c_i.\int_{t_0}^{\infty} (t-t_0)dF(t)$$

$$= c_0 + k.\int_0^{t_0} F(t)dt + c_i.\int_{t_0}^{\infty} (1-F(t)).dt$$

The expected cycle-time is:

$$t_0 + \int_{t_0}^{\infty} [1-F(t)].dt$$

Thus, the expected cost per unit time is:

$$E[C] = \frac{c_0 + k.\int_0^{t_0} F(t).dt + c_i.\int_{t_0}^{\infty} [1-F(t)].dt}{t_0 + \int_{t_0}^{\infty} [1 - F(t)].dt}$$

Repair-Limit Models: One of these models is first applied by Drinkwater and Hastings on army vehicles{Drinkwater and Hastings, 1967}. In their model, they check the situation of the failed unit at a time t_0 and estimate its repair cost. If the estimated cost of repair is larger than a certain amount they delete repair and replace the unit.

An alternative approach is to repair the failed unit, if repair time is short and to replace it, if repair time is long{Nakagawa and Osaki, 1974}. In other words, if repair cannot be completed in a specified period (i.e. the repair-limit time), then the unit is replaced with a new one. The objective is again to minimize the expected cost per unit time for an infinite time span. Considering a cycle-time, from the beginning of the operating unit till the completion of repair (or replacement), the expected cost per unit time, when a repair limit duration of t_o is given, can be expressed as:

$$E[C] = \frac{C_f \cdot \bar{G}(t_o) + \int_o^{t_o} \bar{G}(t).dC_r(t)}{1/\lambda + \int_o^{t_o} \bar{G}(t).dt}$$

where:

C_f = Failure replacement cost of the unit

$\bar{G}(t_o)$ = C.d.function value of repair-times over repair limit time t_o

$G(t)$ = C.d.f. of repair limit times

$\int_o^{t_o} \bar{G}(t).dt$ = Mean time to repair unit, given replacement done at t_o, if repair is not finished till that time.

$dC_r(t)$ = Expected repair-cost + downtime cost incurred at instant dt.

$1/\lambda$= Mean time to failure for the failure distribution F(t).

<u>Replacement Models Combined With Ordering Policies for Spare Units</u>: If Lead-times for replacement parts cannot be neglec-

ted, then ordering policies for spare units would be considered. Wiggins{Wiggins, 1967} considered such an ordering policy where a spare unit is ordered at t_o units of time, after installation of the original unit or at failure of the original unit, whichever one occurs first. Then he minimized the Expected Average Cost function given by the expected inventory and expected shortage costs, by obtaining the optimal re-ordering time t_o.

Wiggins introduced the following costs in his model;

a_1 = Shortage cost/unit time, when the system fails before spare unit is available

a_2 = Inventory cost/unit time, when the spare unit is delivered before needed.

c_1 = Expedited Ordering cost/unit, when the system fails before the fixed ordering time t_o.

c_2 = Normal ordering cost/unit, when ordering at the normal ordering time t_o.

$1/\lambda$ = Mean time to failure for the arbitrary failure distribution F(t).

L = Lead-time for delivery of the spare unit.

Then, the expected cost for each stage is developed into the following formula;

$$E[C] = \frac{a_1 \cdot \int_{t_o}^{t_o+L} F(t).dt + a_2 \cdot \int_{t_o+L}^{\infty} (1-F(t)).dt + c_1 F(t_o) + c_2 .(1-F(t_o))}{1/\lambda + \int_{t_o}^{t_o+L} F(t).dt}$$

The Expected Cost per unit time, given t_o, will be minimized at optimal t_o (the optimal re-ordering time for the spare unit).

Some of the other replacement models take into account additional cost factors as for instance, the costs of keeping a unit operating, as adjustment, depreciation and interest costs{Clearoux and Hanscom, 1974}. There are age replacement policies which take into account primarily the discount factor. Such applications would be feasible for policies planned over longer time horizons, i.e. longer than a year{Fox, 1966}. Some authors assumed replacement only on detection of failure and introduced inspection periods, which would minimize the expected total cost until detection of the failure{Barlow and Proschan, 1965}.

I.3. SCOPE AND ORGANIZATION

This work covers only the wire-drawing machinery in the drawing department of the selected company. It includes sixteen machines and eighteen types of critical components located on these machines. A total of ninetynine components on all machines are considered in this study.

In Chapter II, an overview of the production system is given and the current maintenance practices in the wire-drawing department is reviewed in detail. In Chapter III, the failure data is organized and the critical components are identified. The critical components selected for analysis are coded to enable data-processing application and to aid in presentation. Statistical analysis is performed on the organized failure data, inorder to determine the types of lifetime models relevant for each component. By the end of Chapter III, decisions are taken to delete planned-replacement policy for some components. The decision rule for deletion is simply the failure rate, being monotonically decreasing or remaining constant. The parameters of lifetime models are estimated for the remaining selected components and the adequacy of the models are checked.

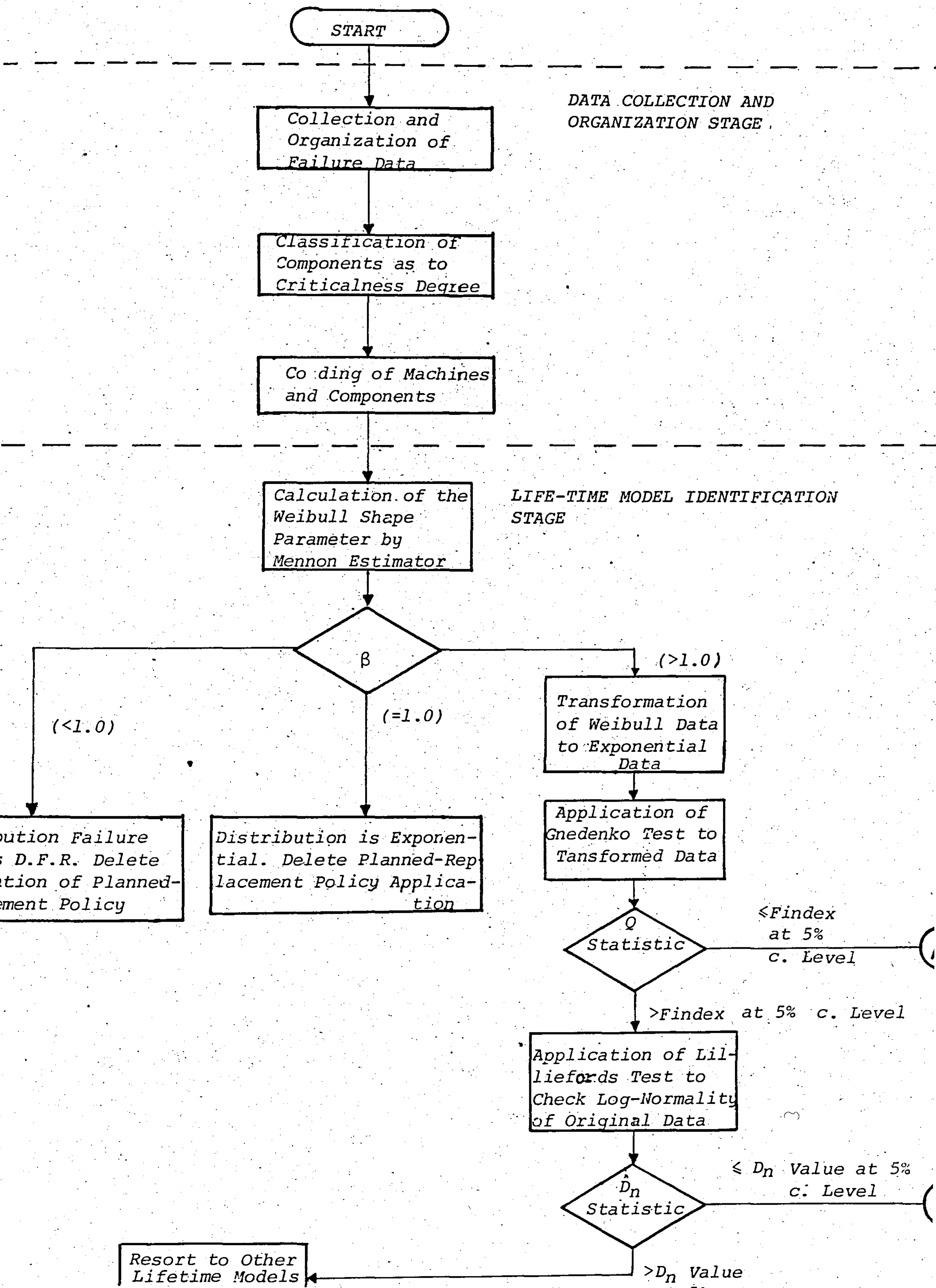
In Chapter IV, expected unit cost formulas applicable to each component type are developed. Material, labor and production-loss costs are calculated for each component both for planned and failure-replacement events. Then, computations for expected costs of the proposed policy per unit time are performed and the optimal planned-replacement periods which minimize the expected unit costs are obtained. Next, a more generalized model, involving minimum production requirements on main-feeder machines, maximum allowable production losses on final drawers and minimum cash budget constraints on failure and planned-replacement periods is constructed. The selection of only one integer variable is imposed for each component, by integrality constraints. An application with the model is carried, by imposition of minimum production requirements on the main-feeder machines and also a cash-budget constraint for failure and planned-replacement activities.

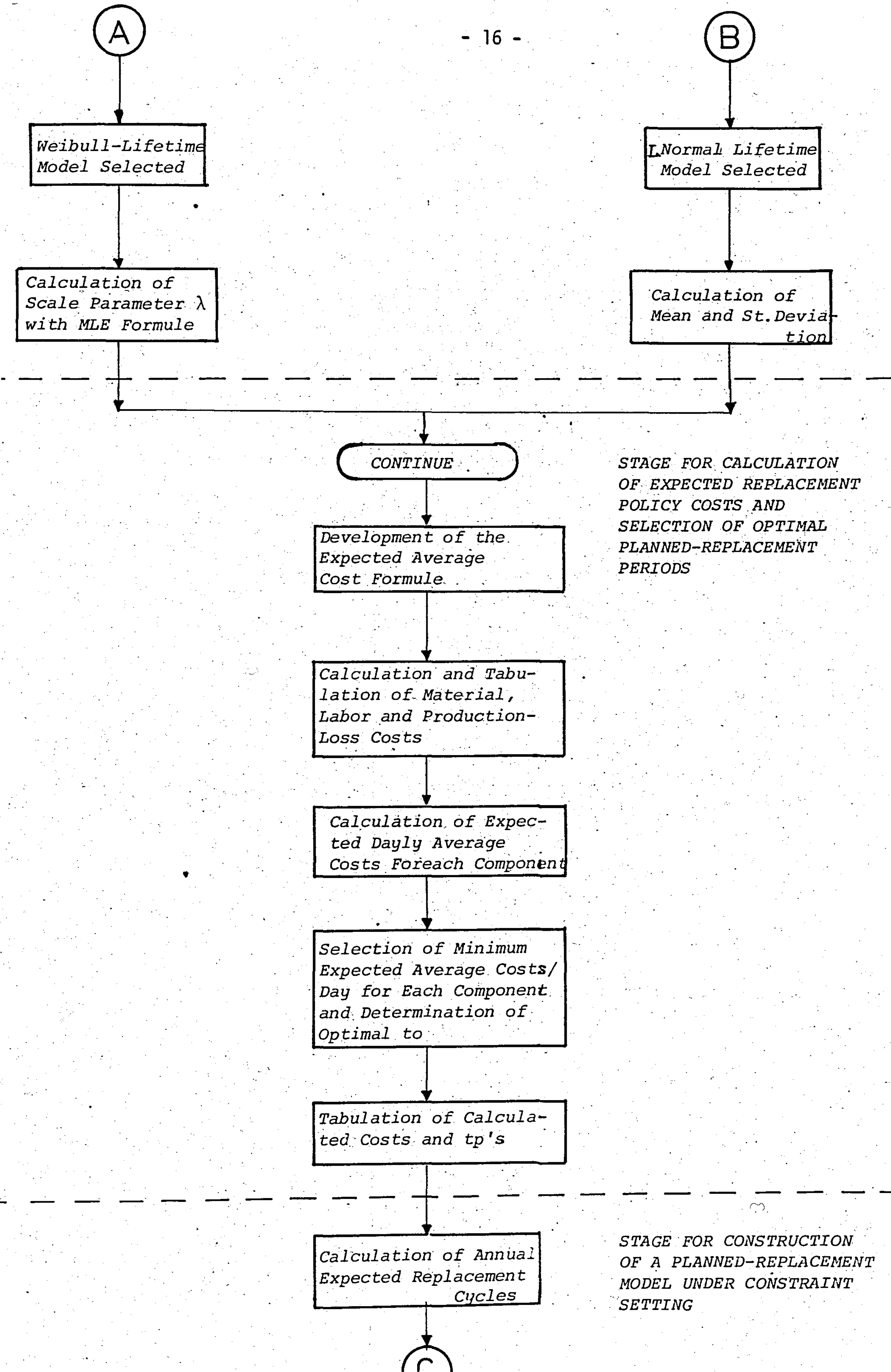
In Chapter V, analysis of solutions related to optimal planned-replacement periods and costs, under non-constraint and constraint settings is performed.

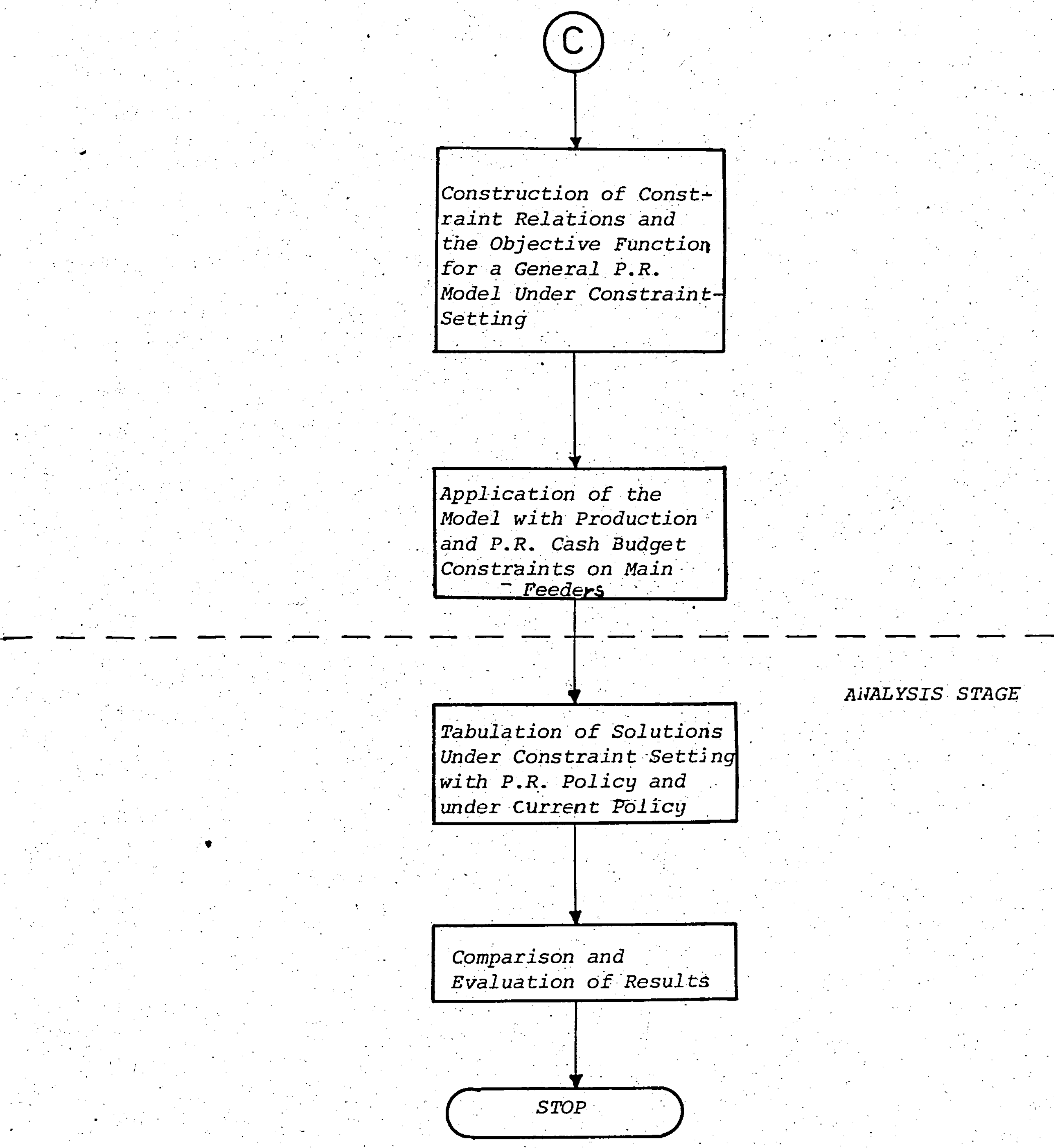
The final chapter involves conclusions and suggestions as to the improvements obtained by the implementation of the proposed model and accounts for possible extensions.

In Figure 1.3, a macro flow-chart for the application of the planned-replacement model is given.

FIGURE 1.3 MACRO-FLOW CHART FOR THE APPLICATION OF THE "PLANNED-REPLACEMENT MODEL"




A
B
Weibull-Lifetime Model Selected
Normal Lifetime Model Selected
Calculation of Scale Parameter λ with MLE Formule
Calculation of Mean and St.Deviation
CONTINUE
STAGE FOR CALCULATION OF EXPECTED REPLACEMENT POLICY COSTS AND SELECTION OF OPTIMAL PLANNED-REPLACEMENT PERIODS
Development of the Expected Average Cost Formule
Calculation and Tabulation of Material, Labor and Production-Loss Costs
Calculation of Expected Dayly Average Costs Foreach Component
Selection of Minimum Expected Average Costs/Day for Each Component and Determination of Optimal to
Tabulation of Calculated Costs and tp's
Calculation of Annual Expected Replacement Cycles
STAGE FOR CONSTRUCTION OF A PLANNED-REPLACEMENT MODEL UNDER CONSTRAINT SETTING
C


C
Construction of Constraint Relations and the Objective Function for a General P.R. Model Under Constraint-Setting
Application of the Model with Production and P.R. Cash Budget Constraints on Main Feeders
ANALYSIS STAGE
Tabulation of Solutions Under Constraint Setting with P.R. Policy and under Current Policy
Comparison and Evaluation of Results
STOP

II. DESCRIPTION OF THE CURRENT SYSTEM

II.1. MATERIAL FLOW AND THE DRAWING PROCESSES WITHIN THE PLANT

Figure 2.1. reflects the direction of material flow together with the dimensions of the drawn wires produced by each type of machine. The approximate daily capacities of each machine are also given in this figure.

As can be observed from Figure 2.1., the drawing machinery in the department are classified under three primary categories, namely: Main Feeder, Intermediate and Final Drawing Machines. The main feeder machines, also called Thick-Wire Drawers, are very vital for the overall drawing operations, since they produce inputs to all other drawing machinery.

A drawing operation consists of the following major phases. First, the feeder-spool gives the wire into the dancer pulleys which lets the wire into the first drawing die at a right-angle. Secondly, the wire is pulled over the Drawing-Head after passing through the first-die and the wire-guide channel. Next, it is fed into the next die at right-angle and fed into the first drawing-capstan. The drawing-capstan lets the wire into the third die at a right angle and then into the second capstan and so forth. The diameter of the wire is reduced at a certain level as it runs through each die, within specified tolerances. Actually, reduction amounts are preset by machinery technical data and are almost standart for each size of wire diameter to be produced. The wire is fed

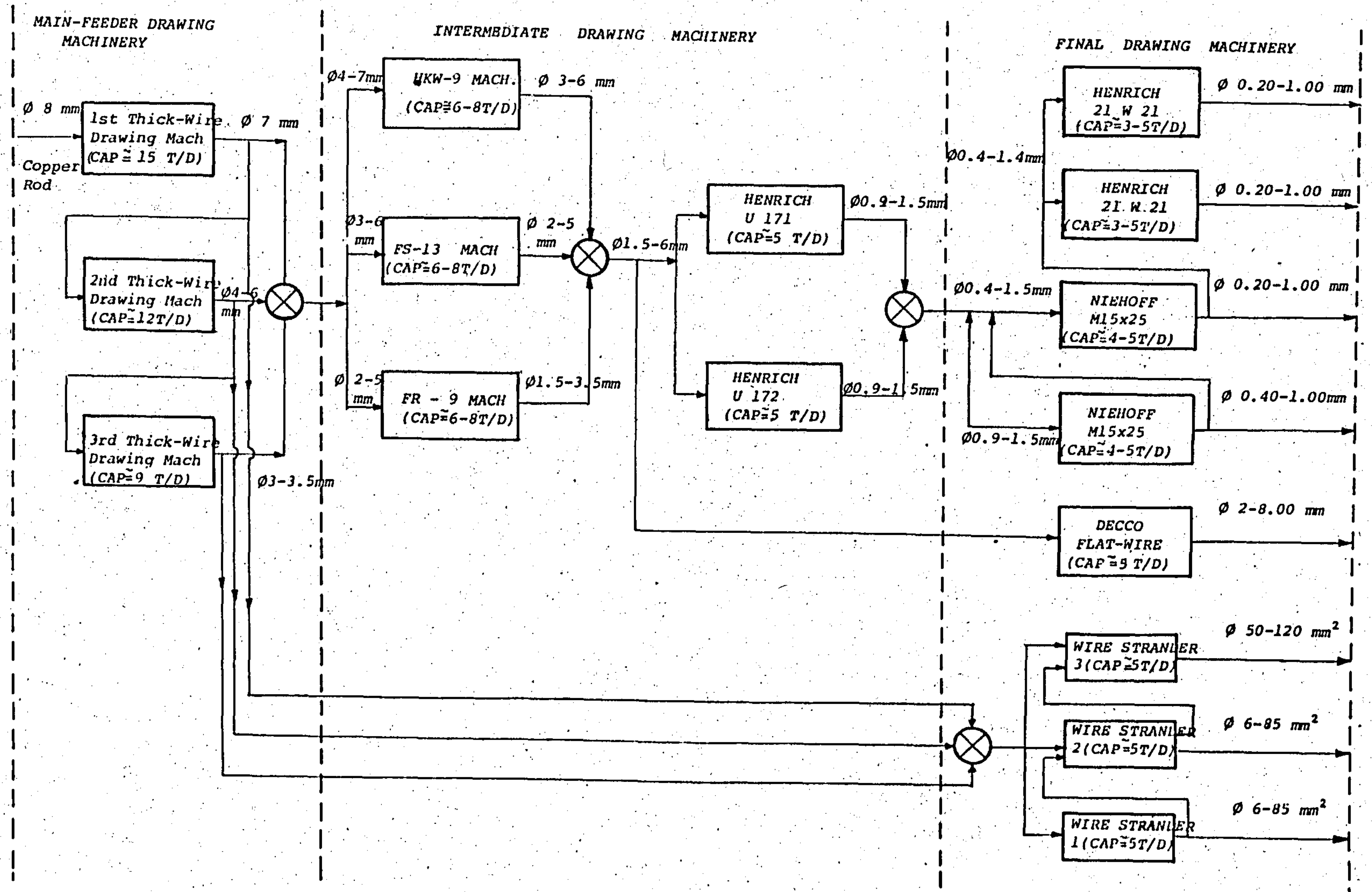


FIGURE - 2.1 MATERIAL-FLOW DIAGRAM

into the capstans several times back and forth before being sent into the final die and over the dancer pulleys after which they are fed into the spooler system. Particularly in those machines, which manufacture very thin wires, the travel of the wire over the same capstans (over its different wire-tracks), may be ten to fifteen times, while the total number of drawing capstans used may range up to twenty.

The tension and heat level is usually very high during the drawing operations, which requires constant cooling by spraying of a special borax and water emulsion onto the moving wire. Sometimes, the wire travels within the emulsion itself. The wire, reduced to its final required diameter is fed into the spooler system, governed by an N-Shalt and variator system which enables proper spooling of the wire.

In those drawing machines, which have automatic heat-treatment system, the drawn wires run into a heat treatment unit after final reduction. In this unit, current is applied at incoming and outgoing ends of the running wire, at low voltage and high intensity. The running of the wire in the heat-treatment unit is over the porcelain pulleys and bridges to prevent short-current damages. To give an idea of the drawing operation, an overview of the drawing head, capstans, dies, feeder spool, along with the dancer pulleys and the final spooler system is illustrated in Figure 2.2.

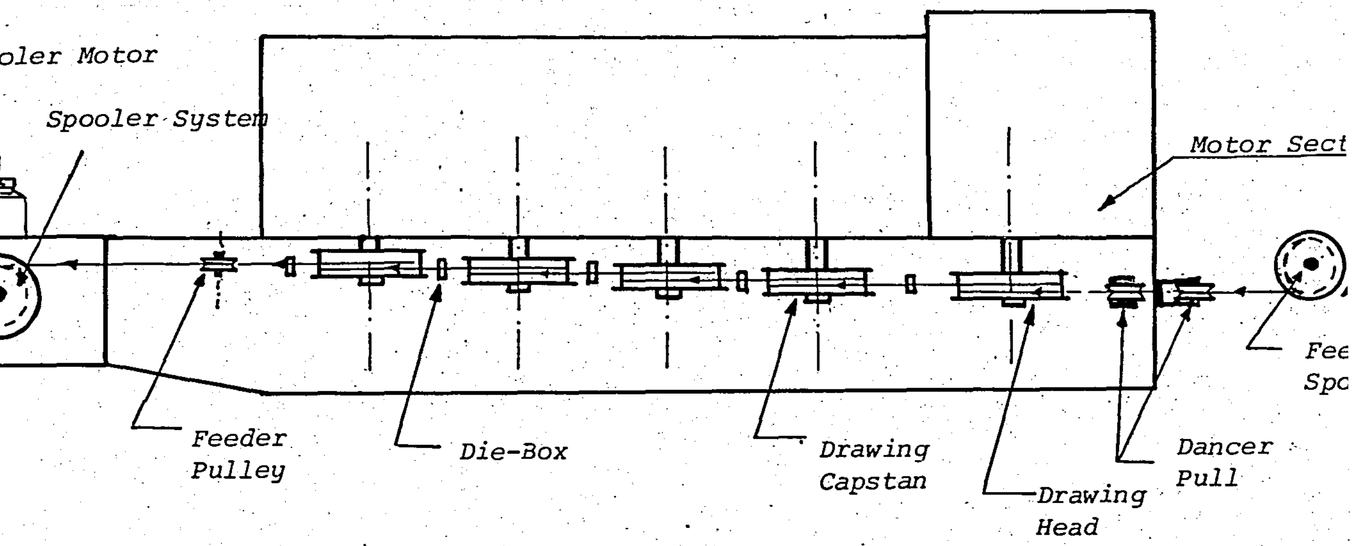


FIGURE 2.2 AN OVERVIEW OF THE MAJOR-DRAWING COMPONENTS IN A 5-DIE AND AUTOMATIC-SPOOLER MACHINE, WITH NO HEAT TREATMENT UNIT.

II.2. CURRENT MAINTENANCE PRACTICES AT THE WIRE-DRAWING PLANT

The company management, being under pressure for continous production in the wire drawing plant carries the general attitude of overlooking at the machine preventive replacement practices. They believe that the machine interruptions for such purpose would mean considerable loss of production. It is thought that repair-on-failure policy is cheaper and more practical than a periodic check-up and planned replacement policy for the drawing machines.

It is observed that some of the machines carry certain measurement devices like voltmeters, ampermeters, oil level and emulsion level indicators, wire breakage signals. However, the operators do not usually react at the right time to such devices. When they react, they simply stop the machine and inform the technical supervisors. The supervisors sometimes forego necessary inspections, unless they are very critical. During night-shifts, the operator check-ups of these devices are at minimum. The machines are connected to automatic control and it is when the wire breakages occur or when the machine totally stops, that the operators would check-up the machines.

The operator warning signals on the drawing machines can be classified as follows;

1- Signals for electrical and electronic equipment (control devices for electrical circuits, termics, N-shalts, potentiometers, voltmeters, ampermeters).

2- Signals for other than electrical and electronic equipment (Speedometers, Oil-pressure, emulsion-level indicators, wire-breakage signals).

By the first group of signals, automatic control is more or less provided for electrical and electronic systems. In fact, in this work, electronic and electrical components are excluded from the critical components list except for N-shalts which are circuit controlling devices for regular functioning of the spooling and variator systems.

There are also some cleaning, oiling and die-maintenance activities on the machines. Especially the die maintenance activities are carried with care. Infact, there's a separate die-repair and maintenance shop equipped with die-inspection microscope, rectification and polishing instruments and die-angle measurements are made between certain drawing-tonnages and necessary angle adjustments, rectifications and polishing work are carried by 2 experts in this room. It should be pointed out that wire surface quality is directly proportional to a proper die-maintenance activity. As to this maintenance activity, the plant management is sensitive and aware of the importance of this component. Thus in this work, "dies" are also excluded from analysis.

Several measures are taken in the plant to repair failing components. These can be summarized as:

1- To keep the frequently failing items such as seals, bolts, nuts, N-Shalts, hoses, sleeves, clutches, filters in the spare part stocks

2- Provision of such material in the in-plant auxiliary depot

3- To keep maintenance personnel in the plant.

Even though such measures have been applied in the drawing department for the last four years, stock scarcities are faced frequently for many critical items. This indicates that critical stock levels are not properly specified in the plant, which causes the purchasing department to buy at high prices for urgent repair needs. For certain other items, undesired stock piling is observed, which leads to unnecessary working-capital tie-up.

A positive approach noted as to the maintenance activities in the plant, is related to failure-information collection.

Machine failures and actions taken to repair the failing components, are recorded into the "Shift-Files" by the technicians.

Currently, five maintenance personnel are employed in the plant, one of which is a qualified technician while others are expert-labourers. It is always possible to provide seven more workers from other departments for repair or replacement operations, if required. Failures are handled in following steps;

1- If it is a small failure, like capstan wear-out (which is handled, when wire-breakage occurs due to the track wear-out in the capstan), the operators will record failure and replace the capstan while the worn-out capstan is sent to repair-shop for renewal.

2- If it is a major failure, like breakdown of shaft or pinion group, the operators warn the head technician and the department chief-engineer about the event. The head engineer informs the factory manager. The machinery is dismounted by a group of workers and technicians, while a listing of the failing components and required number of replacement items is prepared by the technicians. Then starts a search for the existence of required items in Plant Spare-Parts Depot. Another listing is made for non-existing items. These listings, together with causes of break-down are submitted to factory manager. The factory manager contacts General Manager, who in turn instructs the Purchasing Manager for urgent provision of missing items. Also, if required, additional electricians and mechanics from İzmit Plant are requested. The purchasing department usually takes about 3-10 days in order to complete market search and collects offer letters. Meanwhile productions of the failing machinery and related machinery have stopped. This is critical especially for first, second and third thick wire drawers, since intermediate stocking cannot be made for these machines.

Thus, usually a long process takes place before the maintenance people can get their missing parts and start re-assembly. Generally, the results of the current repair or replace-on-failure maintenance policy leads to the following costs;

a) Costs due to Machine Failures;

1- Production-Loss costs due to down-times

2- Quality-Loss costs due to sudden stoppages

3- Production interruption-costs in related machines

4- Idle operator time costs

b) Costs due to Late Handling of Worn-Out Components;

1- Costs related to quicker wear-out of components

2- Costs due to Side-effects of breakage in other components

c) Costs due to Rush-Orders;

1- Purchasing department is obliged to buy at higher costs than normal.

d) Costs due to Failure-Repairs;

1- Failure-repair leads to higher costs then planned replacement, since more damage is incurred usually.

2- More labour time is required for dismounting and replacement activities.

III. STATISTICAL ANALYSIS OF FAILURE-DATA

III.1. DATA COLLECTION AND ORGANIZATION

The raw data for component failures are collected from the plant maintenance files. Data as to the repair and replacement practices are obtained from the chief-engineer of the drawing department, maintenance-supervisor and machine foremen. Also, machinery catalogs and bulletins were used for obtaining information on machines and components.

The criticalness of the components included in our model depends on the following factors;

1- The frequency of its breakdowns,

2- The durations of repair or replacement due to sudden failures,

3- The durations of replacement-periods when planned replacement is applied,

4- The production-loss costs incurred.

The selected components are classified into four primary groups, in line with their degree of criticalness as A, B, C and D types. In Table 3.1, a listing of the critical components, including their code names used in this application is given. In Table 3.2, the main characteristics of each critical component group are summarized. The locations of the major components are illustrated in Figure 3.1.

The organization of failure data is performed in the following manner. For each component, successive failure periods

TABLE 3.1- COMPONENTS USED FOR THE APPLICATION

Code	Name of Component or Component Group	Function of the Component or Component Group on the Machine
001	Drawing Head an Capstan	Drawing wire and feeding into dies or over the pulleys
002	Oil Filters	Filtering machine-oil in the system
003	Emulsion Pump	Pumps borax + water emulsion into spray channels and nozzles
004	Cooler System	Pumps water through cooler pipes in the system
005	Grip	Aids in spooling of wire over the drums
006	Gears + Pinion + Schaft	Connected directly to head and capstans group, produces clockwise turn in this group; also drives spooler system and oil distribution mechanism
007	Automatic Stop Motor	Stops Feeder-Spooler System's Motor, when wire is broken in the system
008	Wire-Induction Bridge	Helps easy running of the wire and also prevents contact of it with metal parts by aid of porcelain bands, in the heat treatment unit
009	Air Ventilsand Channels System	Blows air through its ventils over the drawn wire to dry emulsion and clean any particles remaining on wire surfaces
010	N-Schaft	Aids in automatic spooling of the drawn wire over the drums in an orderly way
011	Variator	Regulates spooling operation and stops final spooler system if breakage occurs
012	Wire Guide Channel	Guides running wire for properly and straight forward feeding into and out-of dies
013	Spooling System	Consists of the spooling mechanism, spooler shaft and gears
014	Mirror	Aids in proper and orderly stranding of wires in the wire-stranding machinery
015	Magnetic Capstan Brake System	Aids in sudden stoppage of the capstans and head when wire is broken by magnetic-brake mechanism

TABLE 3.1- (CONTINUED)

Code	Name of Component or Component Group	Function of the Component or Component Group on the Machine
016	Die-Holder	Holds die in a straight and firm position by aid of a special mechanism
017	Turks Head	Flattens round wire in required rectangular crossection in the flat-wire drawing machine
018	Vee-Belt	Transfers motor-drive movement to vantilators

TABLE 3.2- MAIN CHARACTERISTICS OF CRITICAL COMPONENT-GROUPS

Type or Group of Component	Duration of Replacement Activity		Existence of Production-Loss	
	Failure Replacement	Planned Replacement	Failure Replacement	Planned Replacement
A	< 1 DAY	< 1 HOUR	YES	NO
B	< 1 DAY	> 1 HOUR	YES	YES
C	> 1 DAY	< 1 HOUR	YES	NO
D	> 1 DAY	> 1 HOUR	YES	YES

are carefully recorded and tabulated as in Table 3.3, in increasing order.

TABLE 3.3- "MAGNETIC-GRIP SYSTEM" FAILURE DATA "FOR" FIRST THICK WIRE DRAWING MACHINE

T(I); (Days of Survival Since Last Failure)	14	17	20	22	32	33
FREQUENCY {T(I)}: (Frequency of the Specific Survival Period)	1	1	2	1	2	1

35	36	39	41	42	45	48	55	62
1	1	1	1	1	1	1	1	1

Next, above data is re-organized in fractional days by assuming uniform distribution of failures in each day (e.g. two occurrences were recorded on day 32; it was then recorded as 31.5 and 32 days at next step). This procedure would enable us to index each occurrence as a specific time-interval and in an increasing sequence with i = 1,2,3.......n.

III.2. MENNON ESTIMATORS FOR WEIBULL PARAMETERS

In order to determine the shape and scale parameters of the Weibull lifetime model, several estimator formulas are available such as, "Maximum Likelihood Estimator", "Bain and Antle Estimator" and "Mennon Estimator" formulas. The superiority of the Mennon Estimators with respect to others is primarily that the Q-statistic, which is used for Weibull lifetime model check is found to be closest to the Fisher distribution, when Mennon estimated shape parameter is used. Also, the Mennon Estimator for this parameter is consistent {Thiagarajan and Harris, 1976}. Due to above reasons, only Mennon Estimators are used in this work. The shape parameter β, is estimated as:

$$\hat{\beta} = \frac{1}{\hat{d}}$$

where $\hat{d} = \left\{\frac{6}{\pi^2}\left[\sum_{i=1}^{n} (\ln t_i)^2 - (\sum_{i=1}^{n} \ln t_i)^2/n\right]/(n-1)\right\}^{\frac{1}{2}}$

and t_i's are the ordered failure times of the component analysed and n is the total number of observations.

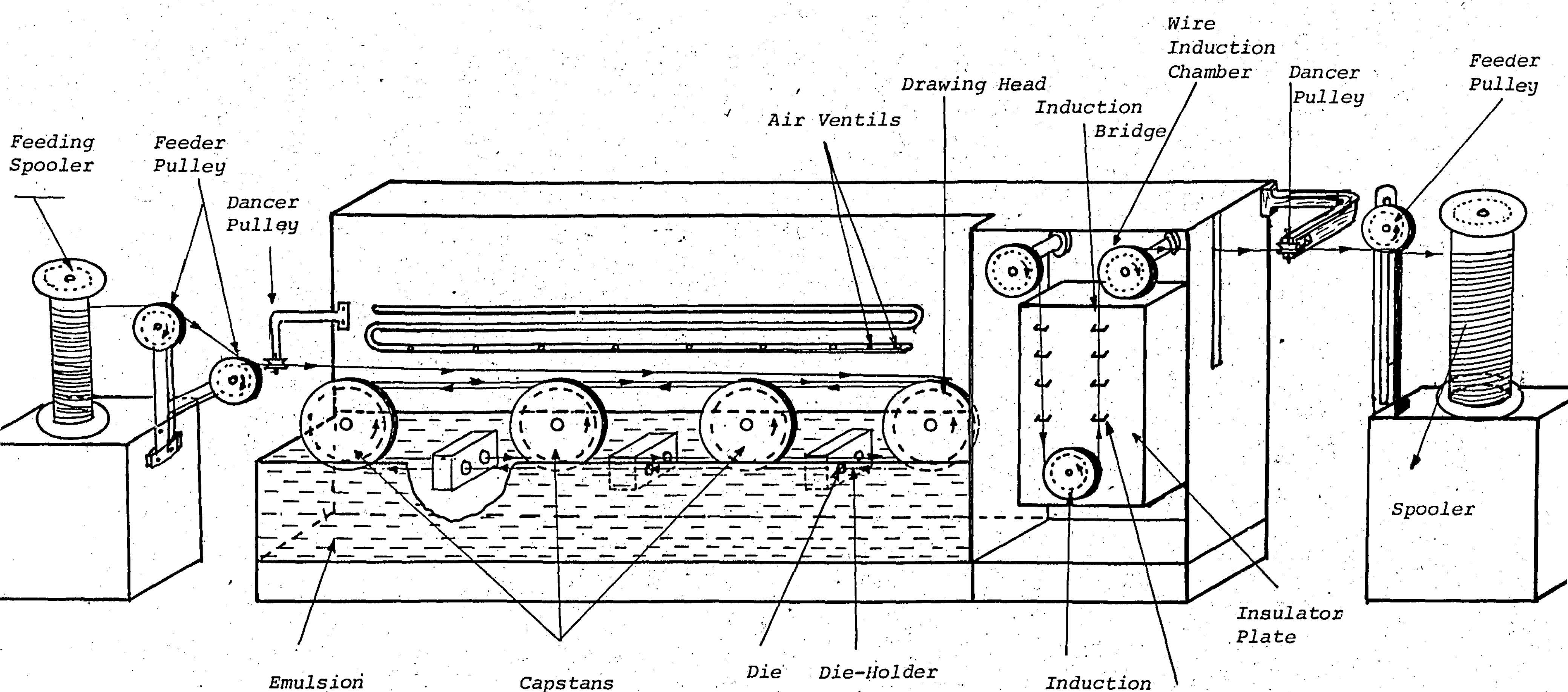


FIGURE 3.1 A CROSS-SECTIONAL VIEW OF A WIRE-DRAWING MACHINE

The scale parameter, β is estimated by employing:

$$\ln\hat{\lambda} = \sum_{i=1}^{n} (\ln t_i/n) - 0.577 \left(\left[\frac{6}{\pi^2(n-1)}\right] \left[\sum_{1}^{n} (\ln t_i)^2 - (\sum_{1}^{n} \ln t_i)^2/n\right]\right)^{\frac{1}{2}}$$

Once $\ln\hat{\lambda}$ is calculated, we derive $\hat{\lambda} = e^{-\ln\hat{\lambda}}$ as the scale parameter estimate{Mann, et.al., 1974}. The shape parameters are calculated for all components in this work and the scale-parameters are calculated for only those components, which pass the Weibull-Check explained in the next section. The shape and scale parameter estimates for those components which have Weibull distribution are displayed in Appendix-3.

III.3. VERIFICATION OF WEIBULL-MODEL

In order to check whether the failure data comes from a Weibull distribution, the following procedure is used:

As explained before, the shape parameter β should be larger than 1.0, to justify a planned-replacement opplication. If the estimated shape parameters are bigger than 1.0, the failure times t_i's from the suspected Weibull population are transformed to exponential times by using the β estimates as: $x_i = t_i^{\hat{\beta}}$.

Gredenko-F test for exponentiality is applied to transformed data at the next step{Thiagarajan and Harris, 1976}. Using the transformed variables, the statistic called the "Q-Statistic" will be calculated as follows:

$$Q(r,n-r) \equiv (1/r) \sum_{i=1}^{r} S_i / (\frac{1}{n-r}) \sum_{i=r+1}^{n} S_i$$

Where, r is taken approximately as half of the total number of observations, n. S_i, called the ith. normalized spacing is calculated by

$$S_i = (n-i+1)\ (x_i - x_{i-1}) \qquad i = 1,2,\ldots n \text{ and } x_0 = 0$$

The resulting Q-statistic is tested against the F-distribution with 2r and 2(n-r) degrees of freedom at α = 5 % critical level. If the Q-Statistic < F-Value at 5 %, the exponentiality of the transformed distribution and thus the Weibull lifetime model is verified.

III.4. TESTING FOR LOG-NORMALITY OF DATA

The log-normality of failure-data is tested, if the check for the Weibull check is negative. The commonly applied method used for the verification of the suspected log-normal p.d.f. is the "Lillieford's Test". In this test, the log-normal failure data are converted into normal data first. Then a statistic called "$\hat{D}$-Statistic" is calculated{Mann, et.al., 1974}:

$$\hat{D}_n = \max\ (\hat{L}_i), \qquad 1 \leq i \leq n;$$

$$\hat{L}_i = \max \left[F_0(l_i;\bar{l};s) - \frac{i-1}{n}\ ,\ \frac{i}{n} - F_0\ (l_i;\bar{l};s) \right]$$

Where $F_0(l_i;\bar{l};s)$ is the cumulative distribution function. If the value of $\hat{D}_n$ is lower than the critical D-statistic value at α = 5 % level, the hypothesis that the failure data comes from a suspected lognormal failure distribution is accepted. In above relations:

l_i = natural log values of observed interfailure periods, t_i

$\bar{l}$ = sample mean of $\log t_i$

s = sample standard deviation of $\log t_i$

n = no of observed interfailure periods in the analysed sample. The results of the LNormality Test are reflected in Appendix-3, which summarizes the means and standard deviations of the verified log-normal distributions.

IV. CONSTRUCTION OF THE PLANNED-REPLACEMENT MODEL

IV.1. COMPUTATION OF THE EXPECTED PLANNED-REPLACEMENT POLICY COSTS AND TOTAL EXPECTED REPLACEMENT CYCLES

The expected age replacement policy cost perunit time can be expressed as:

$$E\{C\} = \frac{C_p\ R(t_p) + C_f\ [1-R(t_p)]}{\int_0^{t_p} R(t).dt} \qquad (4.1)$$

In our analysis, this formula will be used with a slight modification. That is, the integration of R(t) in the denominator is converted into the discrete summation expression as:

$$\sum_{t_i=0}^{t_p} R(t_i) \qquad (4.2)$$

for computational convenience on the computer. A similar approach is made by Ackoff and Sasieni {Ackoff and Sasieni, 1968}. Also, an extension period due to late replacement days (d_i), for the C and D types of components are added to this, expression as:

$$\sum_{t_i=0}^{t_p} R(t_i) + d_i \left[1 - R(t_p)\right] \qquad (4.3)$$

The general unit cost expression utilized in this work is:

$$EDC_{ij}\{t_p\} = \frac{[V_{ij} + CP_{ij}]\ R_{ij}(t_p) + [U_{ij} + CF_{ij}][1 - R_{ij}(t_p)]}{\sum_{t_i=0}^{t_p} R_{ij}(t_i) + d_{ij}[1 - R_{ij}(t_p)]} \qquad (4.4)$$

where

t_p = Planned-replacement period in days

$EDC_{ij}(t_p)$ = Expected Daily Policy Cost for component i of machine j, given planned-replacement period t_p

$R_{ij}(t_p)$ = Reliability function value at t_p, for component i of machine j.

V_{ij} = Production-Loss Cost for planned-replacement event

CP_{ij} = Planned Replacement Material and Labor Cost.

U_{ij} = Production-Loss Cost for failure-replacement event.

CF_{ij} = Failure Replacement Material and Labor Cost.

d_{ij} = Extended days of failure replacement.

The above formula will change slightly for each critical group of components, by dropping some of the coefficients as explained below:

In "A type" of components, where there is no planned-replacement production-loss and no delays in days for failure-replacement, the expressions V_{ij} and $d_{ij}[1-R_{ij}(t_p)]$ will be dropped.

In "B type" of components, where there is no delay in failure-replacement activity, in days, the expression $d_{ij}[1-R_{ij}(t_p)]$ will be dropped.

In "C type" components, where there is no production-loss incurred in planned replacement activities, V_{ij} is dropped and in "D type" of components, the formula is utilized fully. In our study, production-loss effects are considered only for those machines which are in failure state. This assumption is based on the availability of sufficient buffer stocks which can feed the following machines without any interruptions. The details of obtaining material, labor and production loss-costs are explained in detail in Appendix-2. To illustrate how these costs components are identified, we will summarize the procedure used for "1 KATEL/001" coded component which is an A-type of component. The CP_{ij} consists of welding and polishing costs of the inner-wire channels, using maintenance personnel costs. Also, it will include material costs of the newly installed bolts, nuts, special washer and pressure - plates. There is no V_{ij} cost incurred, since, planned-replacement activity takes less than an hour on the average, which means that it can be completed in set-up hour with no production-loss cost incurred.

Minimum expected-Daily Costs and their associated optimal planned-replacement periods (in days) are computed by a program and tabulated in summary form for all components in Appendix-3.

The total number of expected replacement-cycles perannum, $n(t_p)$, is utilized in the constrained planned-replacement model in the next section. The $n(t_p)$ can be defined as the total number of planned and failure replacement cycles per annum, given a planned-replacement period t_p. Generally expressed:

$$n(t_p) = \left(\frac{\text{Work-Program Days}}{\text{Expected Replacement Cycle's Duration}}\right)$$

Where the denominator values are retrieved from equation 4.2 for A and B type of components and from equation 4.3 for C and D type of components. Work-program days is given by the management. In the company studied, the work program days for the wire-drawing department was taken to be 280 days.

IV.2. CONSTRUCTION OF THE GENERAL CONSTRAINT RELATIONS AND THE OBJECTIVE FUNCTION

In this section, the planned-replacement model is generalized by employment of the possible production and budget constraints on the wire-drawing machinery. The selection of the optimal planned-replacement periods can be achieved, from a wide range of possible replacement-periods for each component type, through utilization of the "Mixed-Integer Program Package". A small-sacale application of the general model is explained in Section IV.5.

The generalized model, including the production tonnage requirements for main-feeder drawing machinery, maximum production loss allowances for final drawers and the maximum cash-budget constraint for the application of the planned - replacement policy, can be summarized as follows:

<u>The Objective Function</u>

$$\text{Minimize Annual Policy Cost, } Z_{min} = W \cdot \sum_{j=1}^{J} \sum_{i=1}^{I(j)} \sum_{k=1}^{K(ij)} EDC_{ij}(k) \cdot \tilde{m}_{ijk}$$

where,

m_{ijk} = 1, if planned-replacement is done at period k
0, if planned-replacement is not done at period k

W = Annual work-program days planned for operations

i = Component index (i=1,...,I(j), I=Total no of critical components for machine j.

j = Machine index (j=1,...J), J=Total no of machines

k = planned-replacement period in days, k=1,...,K(i,j)

Subject to;

1- Minimum Production Requirements for Main-Feeder Drawing Machinery

$$\left[W - \sum_{i=1}^{I(j)} \sum_{k=1}^{K(i,j)} n_{ijk} \cdot d_{ij} \left[1 - R_{ij}(k) \right] \cdot m_{ijk} \right] \cdot C_j \geq X_j, \ \forall_j$$

where,

d_{ij} = Failure-replacement period in days for C and D type of components,

C_j = Dayly production capacity for machine j

X_j = Minimum production tonnage requirement for machine j

n_{ijk} = Total number of expected replacement cycles per annum for component i of machine j at period k

$R_{ij(k)}$ = Reliability value at period k, for component i of machine j

2- Maximum Production-Losses Affordable on Final-Drawing Machines

$$\sum_{i=1}^{I(j)} \sum_{k=1}^{K(i,j)} \{U_{ij} \left[1 - R_{ij}(k) \right] + V_{ij} \cdot R_{ij}(k)\} \cdot n_{ijk} \cdot m_{ijk} \leq Y_j$$

where,

U_{ij} = Downtime cost for failure-replacement event for component i of machine j

V_{ij} = Downtime cost for planned-replacement event for component i of machine j

Y_j = Maximum production-loss in TL allowable on machine j

3- <u>Maximum Cash-Budget Allowed for Planned-Replacement Policy</u>

$$\sum_{j=1}^{J} \sum_{i=1}^{I(j)} \sum_{k=1}^{K(i,j)} \{CF_{ij}\left[1-R_{ij}(k)\right] + CP_{ij}.R_{ij}(k)\} \; . \; n_{ijk}.m_{ijk} \leq B$$

where,

B = Cash or out-of Pocket Costs Budget Constaint.

4- <u>Integrality Constraints for (0-1) Integers</u>

$$\sum_{k=1}^{K(i,j)} m_{ijk} = 1 \;\; \forall_{i,j}$$

For computational simplification, the range for the index k of the decision variables m_{ijk} is restricted by some upper bound designated as K(i,j). These values can be determined as

$$K(i,j) = \max \{k; \; R_{ij}(k) \geq \alpha\}$$

Where α value is selected as a small value such as 10-20 %. This rate is basically related to the aging characteristic of the components. Since it is predetermined that the components under investigation are IFR type, the risk of failure is quite high after the survival function R(k) reaches a certain level α. Consequently, it is more advantageous to make the planned replacement before that time.

IV.3. PROBABLE IMPACTS OF CONSTRAINT RELATIONS ON SELECTION OF PLANNED-REPLACEMENT PERIODS

It is beneficial at this point to account for the possible impacts of above constraints on the selection of optimal planned-replacement periods.

As can be observed from Figure 4.1, the impacts of each constraint is reflected as upward or downward movement on the planned-replacement (P.R.) time scale. For increased production requirements, the selection of P.R. period would be at shorter periods (represented by t_p' in the first diagram in Figure 4.1), and under no-constraint setting the selection would be at t_p''. At production tonnages to the left of P", which is the level at non-constraint setting, selection of replacement-periods would be the same. For decreased cash - budget constraints, the selection of the planned-replacement periods would be towards upward direction, represented by t_p' in the second diagram of Figure 4.1. At cash-budget levels to the right hand side of M", which is the cash utilization at non-constraint setting, the selection of the P.R. periods would be the same, as t_p''. The effect of maximum production - losses on P.R. periods would be towards downward direction as the production-loss limits are lowered (represented by t_p' in the third diagram of Figure 4.1). After the P.R. period t_p'', which corresponds to the solution at non-constraint setting, the selection of the P.R. periods would be the same with t_p'', when the production-loss constraint is relaxed.

In Table 4.1, the effects of the model constraints on selection of planned-replacement periods, reliabilities of components, expected number of replacement cycles, failure-replacement downtime days and cash-costs of the planned-replacement policy, are summarized with arrows in upper and lower directions (indicating increases and decreases correspondingly).

TABLE 4.1- EFFECTS OF MODEL CONSTRAINTS, ON SELECTION OF P.R. PERIODS, RELIABILITIES, EXPECTED NO OF REPLACEMENT-CYCLES, FAILURE - REPLACEMENT DOWNTIME DAYS AND CASH-COSTS OF THE P.R. POLICY

N O T E S	Effects of Increased Production Requirements	Effects of Decreased Production Losses	Effects of Decreased Cash-Budget Constraints
1- Planned-Replacement Period (k)	↙	↙	↗
2- Reliability at Selected P.R. Period	↗	↗	↙
3- Expected No of Total Replacement Cycles/Annum	↗	↗	↙
4- Failure Replacement Downtime Days	↙	↙	↗
5- Total Cash Cost of the P.R. Policy	↗	↗	↙

IV.4. APPLICATION OF THE MODEL UNDER CONSTRAINT SETTING FOR MAIN-FEEDERS

A small-size application of the model under constraint setting is carried out by imposing minimum production-tonnage requirements and replacement cash-budget constraints on main-feeder machines, namely the first, second and third thick-wire drawers, coded by 1 KATEL, 2 KATEL and 3 KATEL in this

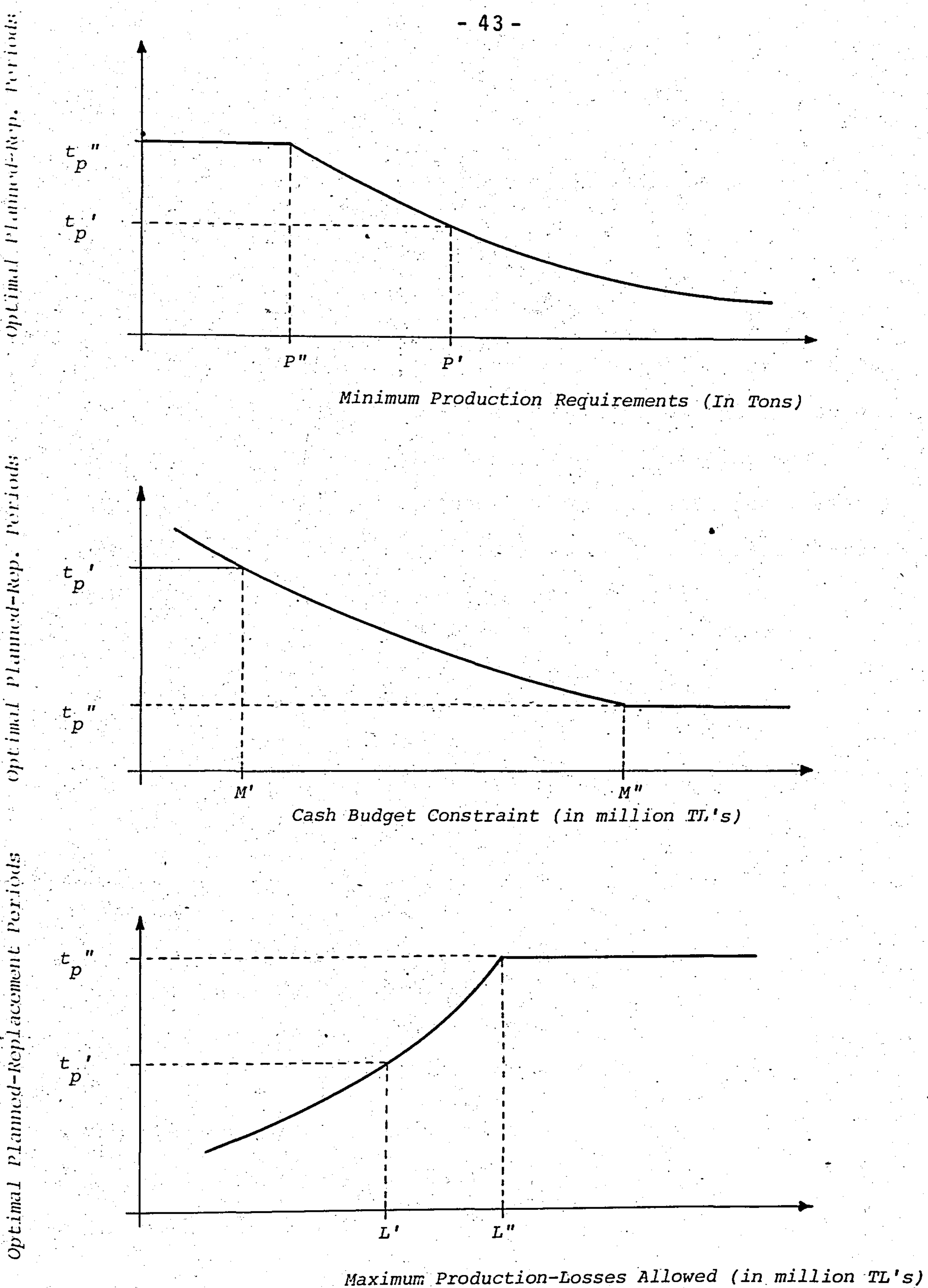


FIGURE 4.1 REFLECTION OF PROBABLE EFFECTS OF MODEL CONSTRAINTS ON SELECTION OF OPTIMAL PLANNED-REPLACEMENT PERIODS

study.

The components involved in this application were:

1- Gear, Pinion and Schaft System

2- Magnetic Capstan Brake System

Both components have failure-replacement periods of more than a day and all have Weibull lifetime models except for second component in 3 KATEL, which has lognormal lifetime model. Also, the failure and planned replacement cash requirements are relatively high for both components. The constraint-relations used in this case are summarized below:

1- <u>Minimum Production Requirement Constraints</u>

$$\{W - \sum_{i=1}^{2} \sum_{k=1}^{K(i,j)} n_{ijk} \cdot d_{ij} \left[1 - R_{ij}(k)\right] \cdot m_{ijk}\} \cdot C_j \geq X_j \quad j = 1,2,3$$

Where,

W = 280 work-program days

C_1 = 15 tons/day for 1 KATEL

C_2 = 12 tons/day for 2 KATEL

C_3 = 9 tons/day for 3 KATEL

X_1 = 3800 tons/annum for 1 KATEL

X_2 = 3100 tons/annum for 2 KATEL

X_3 = 2400 tons/annum for 3 KATEL.

other coefficients are taken from first phase solutions of the computer-program.

2- Maximum Replacement Cash-Budget Constraint

$$\sum_{j=1}^{3} \sum_{i=1}^{2} \sum_{k=1}^{K(i,j)} \{CF_{ij}\left[1-R_{ij}(k)\right] + CP_{ij} \cdot R_{ij}(k)\} \cdot n_{ijk} m_{ijk} \leq B$$

Where,

B = 10.0 million TL/annum

3- Integrality Constraints for (0-1) Integers

$$\sum_{k=1}^{K(i,j)} m_{ijk} = 1, \quad \forall_{i,j}$$

In above, application, K(i,j) periods are given upper limits at those kth periods, where $R_{ij}(k)$ values are at or below 20 % limit.

The objective function is:

$$\text{Min Cost} = \sum_{j=1}^{3} \sum_{i=1}^{2} \sum_{k=1}^{K(i,j)} EDC_{ij}(k) \cdot m_{ijk}$$

Mixed-integer mode of FMPS package program is used on Univac 1106 System to solve the above model, the summary results of which will be presented in the next.

V. ANALYSIS OF SOLUTIONS

V.1. ANALYSIS OF SOLUTIONS UNDER NO-CONSTRAINT SETTING

The solutions taken in the first phase of this study involves optimal planned-replacement periods and related minimum expected costs, under the assumption that there are no production or cash-budget constraints for the operations.

The optimal planned-replacement periods under no constraint setting is obtained with the aid of a computer program, which is run on a Univac 1106 System, in four primary steps:

1- Identification of the Lifetime-models, for components with increasing failure rates and elimination of components with constant or decreasing failure rates.

2- Computation of "Expected Cycle Cost" and "Expected Cycle Duration" for each component, given a set of replacement periods, k=1,...K(i,j), where K(i,j) is the longest inter-failure period observed.

3- Computation of the "Expected Planned-Replacement Policy Cost Per Day", $EDC_{ij}(k)$, for each alternative k'th period.

4- Selection of the minimum $EDC_{ij}(k)$, the corresponding k'th period of which is the optimal planned-replacement period for component i.

The computed dayly expected minimum-costs are multiplied by 280 work-program days, to annualize the cost figures. In order to be able to compare the Planned-Replacement Policy

Costs with Current Policy Costs, the current "Annual Failure-Maintenance Costs" are calculated manually in the following manner:

1- Computation of Failure-Replacement Costs per failure event.

2- Computation of mean failure durations for each component, given its already identified lifetime distribution.

3- Computation of "Average Dayly Failure-Replacement Cost" which is then annualized by multiplying with 280.

In Table 5.1, the computed optimal planned-replacement period periods, minimum planned-replacement and current policy costs together with the annual cost advantages of the proposed policy are tabulated. The annual cost of the current policy is at a level of 348 million TL, whereas the proposed policy cost is at about 261.5 million TL, with an annual cost advantage of about 86.5 million TL.

In Table 5.1, also the lifetime models applicable to each component are summarized. In few cases, some type of components, located in similar type of machines, are observed to have different lifetime models. This discrepancy is mainly due to different work-loads on same components and also due to different models and sizes of these components. The ratios of the mean-failure periods, derived from the lifetime models identified in this work, to the optimal planned-replacement periods are observed to increase as the ratios of failure -

replacement costs to planned-replacement costs increase. For example, for 1 KATEL/001 coded component the mean-failure period to P.R. period is 1.9, whereas the failure-replacement to planned-replacement cost ratio is 6.8. For 13FR9/002 component, the first ratio is 3, whereas the second ratio is 8.5 A summary of above ratios for a number of components is given in Table 5.2.

TABLE 5.1- SUMMARY OF PLANNED-REPLACEMENT POLICY COSTS AND CURRENT POLICY COSTS

(000 TL)

Machine/ Component	Comp. Type	Failure Distrib.	Optimal P.R. Period	MIN. EXP. P.R. Policy Costs Average /Day	MIN. EXP. P.R. Policy Costs Annual	CURRENT F.R. Policy Costs Average /Day	CURRENT F.R. Policy Costs Annual	Annual P.R. Policy Cost Advantages
1 KATEL/001	A	WEIBULL	6	1.5	420	3.6	1.008	
005	A	"	16	0.6	168	0.9	252	
006	D	"	9	65.8	18.424	80.0	22.400	
013	A	"	10	1.6	448	2.0	560	
015	D	"	13	25.0	7.000	31.3	8.764	
016	A	"	16	0.9	252	1.1	308	
018	A	"	22	0.3	84	0.4	112	
					26.796		33.404	6.608
2 KATEL/001	A	WEIBULL	5	3.1	868	4.4	1.232	
005	A	"	13	0.6	168	1.2	336	
006	D	"	15	59.6	16.688	68.7	19.236	
013	A	"	15	0.8	224	1.3	364	
015	D	"	16	18.7	5.236	29.7	8.316	
016	A	"	15	0.6	168	1.1	308	
018	A	"	19	0.2	56	0.5	140	
					23.408		29.932	6.524
3 KATEL/001	A	WEIBULL	5	1.6	448	4.3	1.204	
005	A	LOGNOR.	13	0.5	140	1.2	336	
006	D	"	9	19.7	5.516	68.7	19.236	
013	A	WEIBULL	10	0.8	224	1.3	364	
015	A	LOGNOR.	15	16.8	4.704	29.7	8.316	
016	D	"	15	0.5	140	1.0	280	
018	A	WEIBULL	18	0.2	56	0.5	140	
					11.228		29.876	18.648
8 ORME1/002	A	WEIBULL	15	0.3	84	0.8	224	
006	D	"	21	45.7	12.796	49.2	13.776	
012	A	"	14	0.5	140	1.0	280	
013	A	"	11	0.6	168	1.2	336	
014	A	"	14	0.3	84	0.6	168	
018	A	"	13	0.1	28	0.4	112	
					13.300		14.896	1.596
9 ORME2/002	A	WEIBULL	17	0.3	84	0.9	252	
006	D	"	25	47.7	13.356	51.1	14.308	
012	A	"	14	0.5	140	1.1	308	
013	A	"	10	0.6	168	1.5	420	
014	A	"	9	0.6	168	0.9	252	
018	A	"	14	0.1	28	0.4	112	
					13.944		15.652	1.708

TABLE 5.1- (CONT'D)

Machine/ Component	Comp. Type	Failure Distrib.	Optimal P.R. Period	MIN. EXP. P.R. Policy Costs Average /Day	Annual	CURRENT F.R. Policy Costs Average /Day	Annual	Annual P.R. Policy Cost Advantages
10 ORME3/002	A	LOGNOR.	16	0.4	112	1.0	280	
006	D	WEIBULL	16	104.5	29.260	117.2	32.816	
012	A	"	11	0.6	168	1.6	448	
013	A	"	10	0.7	196	1.8	504	
014	A	"	14	0.7	196	0.9	252	
018	A	"	11	0.3	84	0.7	196	
					30.016		34.496	4.480
11 HKW9/001	A	WEIBULL	3	2.4	672	6.9	1.932	
003	B	"	6	7.3	2.044	10.2	2.856	
004	B	"	6	15.7	4.396	16.5	4.620	
006	D	"	14	103.8	29.064	116.5	32.620	
018	A	"	12	0.9	252	1.6	448	
					36.428		42.476	6.048
12 FS13/001	A	WEIBULL	2	3.2	896	10.8	3.024	
002	A	"	4	2.9	812	4.9	1.372	
003	B	"	11	5.8	1.624	7.2	2.016	
006	D	"	22	67.7	18.956	74.4	20.832	
007	C	LOGNOR.	6	1.7	476	29.3	8.204	
018	A	WEIBULL	12	0.3	84	0.7	196	
					22.848		35.644	12.796
13 FR9/001	A	WEIBULL	3	7.4	2.072	9.0	2.520	
002	A	"	2	3.5	980	5.7	1.596	
003	B	"	8	7.5	2.100	8.5	2.380	
004	B	"	22	17.3	4.844	15.8	4.424	
005	A	LOGNOR.	15	0.5	140	1.2	336	
006	D	EXPONENT.	(NO PLANNED-REPLACEMENT APPLICABLE)					
018	A	WEIBULL	14	0.3	84	0.6	168	
					10.220		11.424	1.204
17 U171/001	A	WEIBULL	3	5.0	1.400	6.0	1.680	
002	A	LOGNOR.	11	0.4	112	1.2	336	
003	B	"	21	2.0	560	3.7	1.036	
006	D	WEIBULL	8	17.2	4.816	55.6	15.568	
008	B	"	14	3.5	980	5.0	1.400	
009	A	"	10	0.3	84	0.7	196	
018	A	"	15	0.4	112	8.0	2.240	
					8.064		22.456	14.392

TABLE 5.1- (CONT'D)

Machine/ Component	Comp. Type	Failure Distrib.	Optimal P.R. Period	MIN. EXP. P.R. Policy Costs Average /Day	MIN. EXP. P.R. Policy Costs Annual	CURRENT F.R. Policy Costs Average /Day	CURRENT F.R. Policy Costs Annual	Annual P.R. Policy Cost Advantages
18 U172/001	D.F.R. (NO PLANNED-REPLACEMENT APPLICABLE)							
002	A	LOGNOR.	16	0.2	56	1.4	392	
003	B	WEIBULL	16	3.3	924	3.4	952	
006	D	"	25	105.1	29.428	115.6	32.368	
008	B	"	16	3.4	952	4.4	1.232	
009	A	LOGNOR.	25	0.1	28	0.4	112	
018	A	WEIBULL	17	0.4	112	0.7	196	
					31.500		35.252	3.752
14 DECCO/002	A	LOGNOR.	10	0.6	168	1.8	504	
003	B	WEIBULL	13	5.9	1.652	11.8	3.304	
017	B	"	10	15.3	4.284	15.5	4.340	
018	A	"	19	0.3	84	0.7	196	
					6.188		8.344	2.156
21 W211/001	A	WEIBULL	4	2.1	588	4.4	1.232	
002	A	LOGNOR.	15	0.2	56	1.4	392	
008	B	"	15	3.2	896	4.5	1.260	
011	B	WEIBULL	13	6.4	1.792	6.6	1.848	
013	A	LOGNOR.	21	0.3	84	0.9	252	
018	A	WEIBULL	14	0.4	112	0.9	252	
					3.528		5.236	1.708
21 W212/001	A	WEIBULL	5	1.6	448	3.8	1.064	
002	A	LOGNOR.	13	0.3	84	1.3	364	
008	B	"	15	3.1	868	4.7	1.316	
011	B	WEIBULL	10	6.4	1.792	7.2	2.016	
013	A	LOGNOR.	17	0.3	84	0.9	252	
018	A	WEIBULL	13	0.15	140	1.0	280	
					3.416		5.292	1.876
19 N1E1/001	A	WEIBULL	4	1.8	504	3.5	980	
002	A	LOGNOR.	14	0.3	84	1.0	280	
006	D	WEIBULL	24	34.4	9.632	37.0	10.360	
008	B	LOGNOR.	16	2.3	644	2.9	812	
009	A	WEIBULL	13	0.2	56	0.6	168	
018	A	"	20	0.4	112	0.7	196	
					11.032		12.796	1.764

TABLE 5.1- (CONT'D)

Machine/ Component	Comp. Type	Failure Distrib.	Optimal P.R. Period	MIN. EXP. P.R. Policy Costs Average /Day	MIN. EXP. P.R. Policy Costs Annual	CURRENT F.R. Policy Costs Average /Day	CURRENT F.R. Policy Costs Annual	Annual P.R. Policy Cost Advantages
20 N1E2/001	A	WEIBULL	7	1.2	336	2.3	644	
002	A	LOGNOR.	12	0.3	84	0.9	252	
006	D	WEIBULL	28	30.2	8.456	32.3	9.044	
008	B	LOGNOR.	20	1.9	532	2.1	588	
009	A	"	15	0.2	56	0.4	112	
018	A	WEIBULL	18	0.4	112	0.7	196	
					9.576		10.836	1.260
					261.492		348.012	86.520

TABLE 5.2- CALCULATED RATIOS OF FAILURE REPLACEMENT COSTS AND MEAN FAILURE PERIODS TO OPTIMAL PLANNED-REPLACEMENT POLICY COSTS AND PERIODS

Machine/Component	Failure Rep. Costs / Planned Rep. Costs	Mean Failure Periods / Optimal Planned Rep. Periods
1 KATEL/001	6.8	1.9
2 KATEL/015	3.5	1.6
3 KATEL/018	6.2	1.8
8 ORME1/012	7.7	1.7
9 ORME2/002	7.3	1.9
10ORME3/014	4.5	1.5
11HKW9/003	2.6	1.4
12FS13/007	100	4.6
13FR9/002	8.5	3
17U171/001	8.5	1.9
14DECCO/002	7	2.0
21W211/008	2.7	1.7
19NIE1/009	7.5	1.9

V.2. ANALYSIS OF SOLUTIONS UNDER CONSTRAINT-SETTING FOR MAIN - FEEDERS

The application of the model under constraint-setting for the most critical drawing machines, the main-feeders, prooved that high production requirements on these machines would shift the optimal planned-replacement periods to earlier periods, while the restrictions on the cash-budget would urge selection of optimal planned-replacement periods at later periods.

A parametric analysis is also carried by altering the degree of the applied production and cash-budget constraints on the main-feeders. The cash-budget utilization and the production tonnages attainable with the optimal replacement periods, calculated under no-constraint setting, is reflected in Trial 0 of Table 5.3. In Trial-1, the minimum production requirements for the first and second thick wire drawers are raised slightly, while the cash-budget is relaxed to 10 million TL. The optimal planned-replacement periods selected under this setting, are relatively shorter than the initial solution, mainly due to decreased down-time days, requiring earlier replacement periods. In Trial-2, the minimum production requirement for first thick wire drawer is raised further, while keeping the production tonnages for the second and third thick-wire drawers and the cash-budget requirement at the same level with Trial-1. The effect of this change is on the replacement periods of components in the first and second thick-wire drawers, urging still shorter optimal replacement-periods. In Trial 3, the minimum production tonnages were kept at the same levels with Trial-1, while the cash-budget limit was decreased to 9 million TL. The solutions for optimal planned-replacement periods were similar to solutions of Trial-1, since the decrease in cash-budget constraint.was not sufficient to produce a shift in the planned-replacement periods. In Trial-4, the minimum production requirements were raised further, while the cash-budget was kept at 10 million TL still. There was no-feasible solution for this trial, since both the cash budget and the production tonnage requirements could not be fulfilled by any alternate selection of the planned-replacement periods. In Trial-5, the cash-budget was lowered to 7.5 million TL, while the production requirement constraints were kept at the same level with Trial-1. The planned-replacement periods for third thick-wire drawer were selected at slightly higher periods for this trial as compared to Trial-1.

Table 5,4 also reflects the daily expected cost values of each trial. In Trial-0, the daily expected cost is 205.600 TL, in Trials-1 and 3, the daily expected costs are 205.700 TL due to slightly raised production requirement constraints. In Trial-2, the daily expected cost is 230.700 TL due to highly restricted production requirement constraints and shortened, planned replacement periods. In Trial-5, the daily expected cost is at 210300 TL. It can be generalized that, in turn for increased production and lesser downtime days, relatively higher daily costs will be incurred by the planned-replacement application as compared to the daily policy costs under no-constraint setting. The same is true when the cash - budget allowances are decreased for the policy application.

TABLE 5.3- SUMMARY INPUT DATA FOR MODEL APPLICATION ON MAIN-FEEDERS

Trials	Cash Budget (In Millions)	Minimum Production Requirements (Tons / Year) 1 KATEL	2 KATEL	3 KATEL
0	(7.8)	(3669)	(3077)	(2486)
1	10	3800	3100	2400
2	10	4000	3100	2400
3	9	3800	3100	2400
4	10	4100	3300	2470
5	7.5	3800	3100	2400

TABLE 5.4- SUMMARY OUTPUT DATA FOR MODEL APPLICATION ON MAIN-FEEDERS

TRIALS	1 KATEL		2 KATEL		3 KATEL		EXPECTED COSTS	
	006	015	006	015	006	015	Daily ('000 TL)	Annual ('000 TL)
0	9	13	15	16	9	15	205,6	57.568
1	9	12	14	15	9	15	205,7	57.596
2	6	12	8	10	9	15	230,7	64.596
3	9	12	14	15	9	15	205.7	57.596
4	NO FEASIBLE SOLUTION OBTAINED							
5	9	12	14	15	12	17	210.3	58.884

VI. CONCLUSIONS AND SUGGESTIONS

VI.1. CONCLUSIONS

This study displays the fact that the application of a planned replacement policy in the wire drawing department of the analysed company, would provide both considerable cost advantages and a systematic approach for the solution of the maintenance problems in this department.

Given the characteristic failure distributions, identified for the critical components studied in this work, the total annual cost of the currently applied "Replace-on-Failure Policy" is at a level of 348 million TL. The application of the proposed policy would maintain a cost advantage of about 86.5 million TL per year, to the company under study, which indicates a cut down of approximately 25 % in the current maintenance-costs and is approximately about 29 % of the net earnings of the company for the year this study is carried. The planned-replacement model was converted into a more general form in Chapter IV. The production requirement constraints and a cash budget constraint was applied on the Main-Feeder Machines to observe the probable impact of these constraints on the selection of optimal planned-replacement periods. The solutions of this application reveals that, as the cash-budget allowance for replacement activities is decreased, the optimal replacement periods will be selected at later periods, whereas when the production tonnage requirements are increased, the optimal planned replacement periods will be selected at earlier periods. The effect of the applied constraints, increase the planned-replacement policy costs slightly. However, the increase in these costs, would not significantly reduce the high cost-advantages of the planned-replacement policy. Thus, even under constraint setting, the planned-replacement application would still maintain very high cost advantages with respect to the current policy. The application of the proposed planned-replacement policy will also lead to other cost advantages which could not be expressed in monetary terms, as reduced scrap costs due to decreased downtime days on the machines, as decreased overhead expenditures due to increased productivity, less idle-times because of decreased failures, lesser overtime costs for maintenance personnel, together with savings due to less rush-orders in the company.

Apart from the above stated cost advantages a much reliable yearly production schedule will be possible due to considerable cutdowns in the number of expected failures in the drawing machinery. Also, the scheduling of the maintenance personnel for the planned-replacement activities will be easier, while the requirement to assign maintenance personnel to night shifts will be decreased.

In the overall, the operations of the wire-drawing department will be improved both with respect to the reduction of the maintenance problems and to the cut down of the annual maintenance costs in this department.

VI.2.2. SUGGESTIONS

For efficient utilization of the proposed planned-replacement policy a follow-up system will be required. A type of identity-card for each component will be prepared involving technical information as to the suggested work-loads and planned replacement periods, service entry dates, failure times and actions taken for each renewal or replacement event.

Extensions of the model are possible in spareparts safety - stock planning and in optimal maintenance personnel planning etc. by using some of the results of the planned-replacement policy. In safety stock planning, the critical parts listing, along with the expected number of replacement cycles per annum, for each component, can be used to calculate the expected yearly parts requirements. In maintenance-personnel planning, knowledge of the expected number of replacement activities would lead to adjustments in the number of current maintenance personnel.

In an extended study, production-loss effects of the stopping machinery on other machinery due to limited intermediate stocks could be considered as an addition to down time costs per failure or planned-replacement activity.

APPENDIX - I

COMPONENT FAILURE - DATA SUMMARY

COMPONENT FAILURE - DATA SUMMARY

MACHINE CODE	COMPONENT CODE	DAYS ELAPSED TILL NEXT FAILURE / N=NO.OF OBSERVATIONS
1 KATEL	001	5 7 7 9 9 9 11 11 11 12 13 13 13 14 16 16 16 16
		16 17 17 17 18 18 18 18 19 19 19 20 20 21 22 22 23
		23 24 25 27 28 / N = 40
	005	14 17 20 20 22 32 32 33 35 36 39 41 42 45 48 55 62
		/ N = 17
	006	6 6 6 8 8 8 9 9 9 9 10 10 10 11 11 11 12 12
		12 12 12 12 13 13 13 14 15 15 15 16 17 17 17 18 19
		19 19 20 22 24 25 / N = 41
	013	6 8 9 11 12 13 15 15 15 15 15 16 16 17 19 19 24
		24 27 29 30 30 31 31 32 32 36 37 37 / N = 29
	015	7 8 8 17 18 19 21 21 22 24 30 32 33 35 35 40 43 43
		44 45 46 50 / N = 22
	016	8 15 21 23 27 28 28 28 29 33 36 54 56 59 60 / N = 15
	018	21 23 28 28 32 40 47 47 54 62 65 67 70 74 77 77 /N=16
2 KATEL	001	4 7 8 10 14 14 22 27 28 29 30 33 35 44 / N = 14

COMPONENT FAILURE - DATA SUMMARY

MACHINE CODE	COMPONENT CODE	DAYS ELAPSED TILL NEXT FAILURE / N=NO.OF OBSERVATIONS
2 KATEL	005	16 18 20 23 23 26 26 26 27 27 29 33 36 43 49 52 / N=16
	006	7 13 14 16 16 16 19 22 24 24 31 32 32 40 / N = 14
	013	11 21 22 24 25 28 28 31 33 35 36 40 41 43 50 62 / N=16
	015	14 18 23 23 23 27 28 30 30 31 32 35 36 37 38 39 44
		56 / N = 18
	016	11 20 24 28 30 31 31 31 32 35 37 41 44 45 46 50 56 /
		N = 17
	018	25 29 29 32 38 38 42 49 54 55 66 69 77 / N = 13
3 KATEL	001	6 8 14 16 18 18 20 21 21 24 26 28 32 35 / N = 14
	005	17 18 20 22 23 24 24 24 24 25 25 27 28 31 33 39 44 /
		N = 17
	006	11 14 17 17 19 19 19 19 20 20 22 24 24 26 29 35 /N =16
	013	16 18 18 19 20 20 21 22 24 27 29 30 41 46 49 / N = 15
	015	16 18 25 25 28 28 30 30 32 32 32 32 35 37 / N = 14
	016	14 21 25 29 32 34 34 36 36 36 36 37 40 42 47 54 / N=16

COMPONENT FAILURE - DATA SUMMARY

MACHINE CODE	COMPONENT CODE	DAYS ELAPSED TILL NEXT FAILURE / N=NO.OF OBSERVATIONS
3 KATEL	018	19 19 22 26 30 30 37 41 49 54 55 57 62 65 66 71 /N =16
8 ORME1	002	21 25 29 32 32 35 38 41 49 54 60 69 / N = 12
	006	8 10 13 16 20 21 23 23 25 29 31 36 39 / N = 13
	012	14 20 27 30 33 33 36 39 43 46 53 / N = 11
	013	12 17 23 28 30 33 34 36 41 46 51 56 60 / N = 13
	014	17 20 23 24 25 25 27 31 34 39 43 49 52 60 / N = 14
	018	26 27 29 29 32 36 39 41 54 62 71 76 80 / N = 13
9 ORME2	002	24 28 32 34 36 36 37 38 40 44 56 59 64 66 72 / N = 15
	006	11 15 17 21 21 24 24 25 28 36 43 54 65 / N = 13
	012	16 23 26 27 30 32 32 32 42 45 49 53 58 64 / N = 14
	013	13 16 19 22 28 28 30 30 30 30 32 37 44 56 64 / N = 15
	014	9 11 15 18 22 24 24 26 29 37 42 49 56 / N = 13
	018	30 30 31 32 35 39 46 54 60 66 69 74 79 86 / N = 14

COMPONENT FAILURE - DATA SUMMARY

MACHINE CODE	COMPONENT CODE	DAYS ELAPSED TILL NEXT FAILURE / N=NO.OF OBSERVATIONS
10 ORME3	002	18 29 30 30 34 35 37 41 42 44 / N = 10
	006	3 5 7 8 9 9 11 13 15 19 20 20 21 22 22 23 24 24
		24 25 / N = 20
	012	11 19 25 28 29 29 29 30 31 32 42 / N = 11
	013	11 19 20 32 33 33 34 35 36 38 / N = 10
	014	16 18 20 22 22 24 29 33 36 41 54 / N = 11
	018	19 22 22 26 29 35 44 48 56 61 72 78 / N = 12
11 HKW9	001	3 5 8 8 11 11 12 12 12 14 14 14 14 16 16 19 26/N=17
	003	6 8 9 10 10 10 10 11 11 13 15 17 20 / N = 13
	004	4 7 7 8 8 8 8 9 9 9 12 14 17 22 / N = 14
	006	3 5 6 6 14 14 15 15 17 17 17 17 18 20 21 / N = 15
	018	16 18 20 20 22 26 29 36 39 47 56 63 69 / N = 13
12 FS13	001	4 4 5 6 7 7 8 8 9 10 10 12 12 13 15 21 /N=16
	002	2 6 6 7 7 9 10 10 11 11 11 13 14 14 14 14 16 16

COMPONENT FAILURE - DATA SUMMARY

MACHINE CODE	COMPONENT CODE	DAYS ELAPSED TILL NEXT FAILURE / N=NO.OF OBSERVATIONS
12 FS13	002	20 20 21 22 23 / N = 23
	003	7 12 13 14 14 18 19 20 23 24 28 32 34 35 / N = 13
	006	8 16 16 17 23 35 37 42 44 47 / N = 10
	007	16 18 18 24 25 28 30 31 32 32 35 40 / N = 12
	018	19 24 26 29 32 38 46 51 62 67 76 81 / N = 12
13 FR9	001	1 3 4 7 8 8 9 9 9 10 11 12 14 27 28 30 32
		32 / N = 18
	002	3 3 4 6 6 6 6 7 7 7 7 8 9 9 9 10 10 11
		12 13 14 17 20 20 20 31 34 / N = 27
	003	5 8 9 10 11 13 13 14 14 15 16 17 26 27 32 46 / N=16
	004	1 4 5 7 7 9 13 14 16 17 21 22 25 25 26 32 / N=16
	005	23 23 23 23 24 25 30 32 35 / N = 9
	006	2 6 10 15 21 23 30 44 56 56 59 / N = 11
	018	19 24 26 29 32 38 46 51 62 67 76 81 / N = 12

COMPONENT FAILURE - DATA SUMMARY

MACHINE CODE	COMPONENT CODE	DAYS ELAPSED TILL NEXT FAILURE / N=NO.OF OBSERVATIONS
14DECCO	002	13 13 16 16 21 21 22 22 23 23 23 24 24 30 / N = 14
	003	12 12 13 14 15 29 30 32 34 38 54 / N = 11
	017	5 6 7 8 10 13 15 16 17 17 18 / N = 11
	018	27 30 32 37 41 48 50 57 64 69 77 81 / N = 12
17 U171	001	1 3 4 7 7 7 8 8 9 9 10 11 12 13 14 15 16
		31 58 / N = 19
	002	14 22 25 29 29 30 32 32 34 34 46 / N = 11
	003	23 26 29 29 29 31 32 32 38 40 42 / N = 11
	006	10 16 22 23 24 25 26 31 32 34 37 / N = 11
	008	10 17 20 24 28 29 29 29 30 31 32 32 / N = 12
	009	16 20 28 30 31 32 32 61 65 / N = 9
	018	20 23 23 26 28 33 37 44 49 57 64 69 74 79 / N = 14
18 U172	001	1 1 3 4 6 8 8 9 10 10 10 11 11 12 14 14 15
		16 17 17 20 20 22 23 27 / N = 25

COMPONENT FAILURE - DATA SUMMARY

MACHINE CODE	COMPONENT CODE	DAYS ELAPSED TILL NEXT FAILURE / N=NO.OF OBSERVATIONS
18 U172	002	21 24 25 26 26 26 27 27 27 28 28 28 29 29 30 30 30
		34 35 37 37 / N = 21
	003	14 19 19 27 29 29 30 34 37 40 48 / N = 11
	006	3 7 7 8 9 10 11 12 14 15 20 22 23 30 34 49 / N=16
	008	20 27 27 29 29 30 31 31 31 32 34 34 35 36 38 38 41
		43 57 / N = 19
	009	32 36 37 41 47 47 48 50 51 52 53 56 / N = 12
	018	25 25 26 28 29 34 39 44 48 52 57 63 69 71 76 / N = 15
19 NIE1	001	5 7 8 10 10 12 12 12 12 12 13 16 17 21 32 / N = 15
	002	16 24 25 27 27 28 29 30 30 30 30 31 33 34 39 41 / N=16
	006	14 16 23 28 30 30 32 32 32 34 38 44 / N = 12
	008	18 21 23 23 25 25 25 25 27 31 36 37 46 / N = 13
	009	18 22 26 26 28 28 28 29 34 38 44 47 54 56 / N = 14
	018	26 28 31 35 39 46 49 53 64 70 76 81 / N = 12

COMPONENT FAILURE - DATA SUMMARY

MACHINE CODE	COMPONENT CODE	DAYS ELAPSED TILL NEXT FAILURE / N=NO.OF OBSERVATIONS
20 NIE2	001	6 8 15 15 17 17 17 18 18 20 20 22 24 27 34 41 /N=16
	002	17 23 26 26 28 31 34 37 40 44 52 / N = 11
	006	15 17 26 27 33 33 36 36 37 39 40 41 47 49 / N = 14
	008	23 25 28 28 30 30 31 33 38 45 49 51 54 59 / N = 15
	009	21 24 27 27 29 29 29 29 33 33 35 38 42 44 50 56 /
		N = 16
	018	25 25 27 29 31 36 39 43 47 58 63 68 72 79 / N = 14
21 W211	001	5 7 9 11 11 11 13 16 19 23 26 31 / N = 12
	002	18 23 25 25 28 28 28 30 30 30 30 31 31 33 36 / N = 15
	008	16 21 21 23 23 24 24 24 26 31 33 34 / N = 12
	011	7 10 11 12 16 16 17 23 25 29 32 35 36 / N = 13
	013	23 34 40 42 43 47 48 49 51 52 53 53 57 59 67 / N = 15
	018	22 22 23 24 27 31 33 38 42 47 54 59 63 69 73 / N = 15
21 W212	001	6 8 13 13 15 15 15 15 16 18 22 29 34 / N = 13

COMPONENT FAILURE - DATA SUMMARY

MACHINE CODE	COMPONENT CODE	DAYS ELAPSED TILL NEXT FAILURE / N=NO.OF OBSERVATIONS
21 W212	002	19 22 27 27 29 29 30 32 34 36 41 / N = 11
	008	17 20 22 22 24 24 24 24 27 30 35 / N = 11
	011	8 11 13 13 15 15 15 15 18 20 23 32 / N = 12
	013	24 30 41 49 52 52 53 59 60 / N = 9
	018	19 22 23 25 29 33 37 44 49 63 67 73 79 / N = 13

APPENDIX-II

COST-DATA SUMMARY

NOTES ON CALCULATION OF COMPONENTS' PLANNED AND FAILURE REPLACEMENT COSTS

CODE/NAME OF COMPONENT	CLASS OF COMPONENT	N O T E S
001/Drawing Headand Capstan	A Type	CP_{ij} consists of welding and polishing costs of inner wire channels using maintenance personnel costs. Also includes change of bolts and nuts if they are worn out. No loss of production incurred during P.R.activity. CF_{ij} consists of same costs as CP_{ij}, U_{ij} will involve downtime cost for 1 hour for HKW-9, FS-13, FR-9, and 1/2 hour for others.
002/Oil Filters	A Type	CP_{ij} consists of clean-up of dismantled filters using maintenance personnel costs. Clean-up is performed by spraying 18 p.s.i. air and wash up by kerosene.
003/Emulsion Pump	B Type	CP_{ij} consists of graphite seal costs, renewed pin costs and maintenance personnel costs. Downtime cost for 1/2 hour is incurred during planned replacement. CF_{ij} consists of same costs as CP_{ij}. U_{ij} includes 1.5 hours' downtime cost.
004/Cooler System	B Type	CP_{ij} consists of change up costs of graphite seals + 0 - rings in the Drawing capstans + replacement costs of couplings and dripping flanges using maintenance personnel costs. Planned-replacement uses both set-up + operational hours. Operational hour used is $\sim$ 1 hour. CF_{ij} is close to CP_{ij}. U_{ij} is about 2 hours' of downtime cost.

NOTES ON CALCULATION OF COMPONENTS' PLANNED AND FAILURE REPLACEMENT COSTS

CODE/NAME OF COMPONENT	CLASS OF COMPONENT	N O T E S
005/Grip	A Type	CP_{ij} consists of grip-spring and pin change-up costs. Change of bolts and nuts and maintenance personnel costs. No production loss cost incurred during P.Replacement CF_{ij} is close to CP_{ij} costs. However production loss-cost is about for ∿ 1/2 an hour.
006/Gears, Pinion and Shafts System	D Type	CP_{ij} consists of change up of worn-up gears, of gear-pins, greasing, bearings. Planned replacement production-loss cost, v_{ij}, is for 10 hours. CF_{ij} consists of change up of worn-up gears, pins, all shaft bearings. u_{ij} consists of 1.5 days' production-loss cost.
007/Automatic Stop Motor	C Type	CP_{ij} consists of renewal of motor coils, change up of motor brushes etc. with maintenance personnel costs. P. Replacement causes 1/2-1 hour of production-loss cost. CF_{ij} consists of almost same costs with CP_{ij} plus complete change up of all brushes, wiring and switches. U_{ij} downtime costs for 1.1 days.
008/Wire-Induction Bridge	B Type	CP_{ij} consists of change up of worn-out brass bridges and porcelain insulators; takes ∿ 1/2 hours from operational period. CF_{ij} consists of same costs and additional costs of change-up of all bridges. Production loss cost is incurred for 1 1/2 hours.

NOTES ON CALCULATION OF COMPONENTS' PLANNED AND FAILURE REPLACEMENT COSTS

CODE/NAME OF COMPONENT	CLASS OF COMPONENT	NOTES
009/Air Ventils and Channels	A Type	CP_{ij} consists of cleaning-up costs of air ventils and channels. CF_{ij} almost same with CP_{ij}, U_{ij} involves production-loss cost of 1/4 hour.
010/N-Schalt	A Type	CP_{ij} consists of clean-up and renewal of end-bits No Loss-of production incurred. CF_{ij} consists of complete change-up of the component + downtime cost of ∿ 1 hour.
011/Variator	B Type	CP_{ij} consists of change-up of weak-coils, clean-up and adjustment. Downtime cost is for 1/2 hour. CF_{ij} consists of change-up of complete variator. Downtime cost is for ∿ 1 hour with failure replacement.
012/Wire-Guide Channels	A Type	CP_{ij} consists of renewal costs of wire channels at no downtime costs. CF_{ij} consists of above costs. Failure downtime costs consists of 1/2 hour's production-loss cost.
013/Spooling System	A Type	CP_{ij} consists of change up of arm-pins and grearing at no loss of-production. CF_{ij} consists of change up of bearings, arm-pins and greasing. Downtime cost incurred at failure is for 1/2 hour.
014/Mirror	A Type	CP_{ij} consists of renewal of mirror at no loss of production. CF_{ij} consists of complete change up of the mirror. Failure replacement causes 1/4 hours' downtime cost.

NOTES ON CALCULATION OF COMPONENTS' PLANNED AND FAILURE REPLACEMENT COSTS

CODE/NAME OF COMPONENT	CLASS OF COMPONENT	NOTES
015/Magnetic Capstan Clutch and Brake	D Type	CP_{ij} consists of demounting and re-coiling costs. Planned replacement leads to loss of production for ∿ 5 hours. CF_{ij} involves complete change-up of all coiling, plates. Failure replacement takes ∿ 1.2 days' period.
016/Die-Holder	A Type	CP_{ij} consists of change up costs of bolts, nuts, washers, adjustment springs and plates. No downtime cost incurred at planned replacement. CF_{ij} consists of above costs; u_{ij} involves dowtime cost of 1/2 hours.
017/Turkshead	B Type	CP_{ij} consists of change up of bearings adjustment springs and plates and polishing costs of inner surfaces. 1 Hour's downtime incurred with planned replacement. CF_{ij} cost involves above costs and complete renewal of the component. Downtime incurred is 2 hours with failure replacement.
018/Vee-Belt	A Type	CP_{ij} consists of belt-stretch adjustment, oil and emulsion cleaning with abundant water. No downtime incurred with planned replacement. CF_{ij} consists of complete change-up of the belt and adjustment-cost. Downtime cost incurred is ∿ 1/4 hours with failure replacement

Machine Code	Component Code	Component Type	P.M. Material & Labour Costs C_p	P.M. Downtime Cost V	F.M. Material & Labour Costs C_f	F.M. Down-time Cost U	F.M. Down-time Days d	F.M. Daily Downtime Cost K	Name of Component or Subsystem
1 KATEL	001	A	6.000	-	11.000	30.000	-	-	Drawing Head and Capstans Group
	005	A	7.000	-	7.000	15.000	-	-	Wire-Grip
	006	D	80.000	300.000	90.000	-	1.5	420.000	Geaus, Pinions and Schafts System.
	013	A	10.000	-	12.000	15.000	-	-	Spooling System
	015	D	15.000	150.000	16.000	-	1.2	420.000	Magnetic Capstan Grip and Brake
	016	A	8.000	-	8.000	15.000	-	-	Die-Holder
	018	A	4.000	-	7.000	7.500	-	-	Vee-Belt
2 KATEL	001	A	7.000	-	10.000	40.000	-	-	Drawing Head and Capstans Group
	005	A	6.000	-	6.000	20.000	-	-	Wire Grip
	006	D	75.000	440.000	80.000	-	1.6	560.000	Gear, Pinions and Shafts System
	013	A	8.000	-	10.000	20.000	-	-	Spooling System
	015	D	13.000	200.000	14.000	-	1.3	560.000	Magnetic Capstan Grip and Brake
	016	A	6.000	-	6.000	20.000	-	-	Die-Holder
	018	A	3.000	-	6.000	10.000	-	-	Vee-Belt

Machine Code	Component Code	Component Type	P.M. Material & Labour Costs C_p	P.M. Downtime Cost V	F.M. Material & Labour Costs C_f	F.M. Down-time Cost U	F.M. Down-time Days d	F.M. Daily Downtime Cost K	Name of Component or Subsystem
3 KATEL	001	A	5.000	-	6.000	50.000	-	-	Drawing Hd and Capstan
	005	A	5.000	-	5.000	25.000	-	-	Wire-Grip
	006	D	80.000	550.000	90.000	-	1.4	700.000	Gears, Pinions and Schafts System
	013	A	6.000	-	10.000	25.000	-	-	Spooling System
	015	D	10.000	200.000	12.000	-	1.2	700.000	Magnetic Capstan Grip and Brake
	016	A	5.000	-	5.000	25.000	-	-	Die-Holder
	018	A	3.000	-	6.000	12.500	-	-	Vee-Belt
8 ORME 1	002	A	3.000	-	3.000	20.000	-	-	Oil Filters
	006	D	90.000	400.000	90.000	-	1.3	480.000	Gears, Pinions and Schafts Syst.
	012	A	5.000	-	5.000	20.000	-	-	Wire-Guide Channels
	013	A	4.000	-	8.000	20.000	-	-	Spooling System
	014	A	3.000	-	3.000	10.000	-	-	Mirror
	018	A	1.000	-	2.500	10.000	-	-	Vee-Belt

Machine Code	Component Code	Component Type	P.M. Material & Labour Costs C_p	P.M. Downtime Cost V	F.M. Material & Labour Costs C_f	F.M. Down-time Cost U	F.M. Down-time Days d	F.M. Daily Downtime Cost K	Name of Component or Subsystem
9 ORME 2	002	A	4.000	-	4.000	25.000	-	-	Oil Filters
	006	D	95.000	500.000	95.000	-	1.4	600.000	Geurs, Pinions and Schafts Syst.
	012	A	5.000	-	5.000	25.000	-	-	Wire-Guide Channels
	013	A	4.000	-	8.000	25.000	-	-	Spooling System
	014	A	3.000	-	3.000	12.500	-	-	Mirror
	018	A	1.000	-	3.000	12.500	-	-	Vee-Belt
10 ORME 3	002	A	5.000	-	5.000	27.500	-	-	Oil Filters
	006	D	100.000	550.000	100.000	-	1.5	660.000	Geaurs, Pinions and Schafts Syst.
	012	A	5.000	-	5.000	27.500	-	-	Wire-Guide Channels
	013	A	5.000	-	9.000	27.500	-	-	Spooling System
	014	A	4.000	-	4.000	14.000	-	-	Mirror
	018	A	2.000	-	4.000	14.000	-	-	Vee-Belt
11 HKW 9	001	A	4.000	-	4.000	50.000	-	-	Drawing Head and Capstan
	003	B	8.000	25.000	10.000	75.000	-	-	Emulsion Pump.
	004	B	9.000	50.000	9.000	100.000	-	-	Cooler System

Machine Code	Component Code	Component Type	P.M. Material & Labour Costs C_p	P.M. Downtime Cost V	F.M. Material & Labour Costs C_f	F.M. Down-time Cost U	F.M. Down-time Days d	F.M. Daily Downtime Cost K	Name of Component or Subsystem
11 HKW 9	006	D	55.000	500.000	80.000	-	1.4	600.000	Gears Pinion, Schafts Syst.
	018	A	7.000	-	10.000	25.000	-	-	Vee-Belt
12 FS 13	001	A	4.000	-	4.000	60.000	-	-	Drawing Head and Capstan
	002	A	6.000	-	8.000	30.000	-	-	Oil Filter
	003	B	7.500	30.000	8.000	90.000	-	-	Emulsion Pump.
	006	D	60.000	600.000	90.000	-	1.6	720.000	Gears, Pinions and Schafts Syst
	007	C	8.000	-	8.000	-	1.1	720.000	Automatic Stop Motor
	018	A	2.000	-	5.000	15.000	-	-	Vee-Belt
13 FR 9	001	A	5.000	-	5.000	50.000	-	-	Drawing Head and Capstan
	002	A	4.000	-	9.000	25.000	-	-	Oil Filter
	003	B	8.000	25.000	10.000	75.000	-	-	Emulsion Pump
	004	B	9.000	50.000	12.000	100.000	-	-	Water Cooling System
	005	A	6.000	-	6.000	25.000	-	-	Wire-Grip
	006	D	60.000	500.000	90.000	-	1.2	600.000	Gears, Pinions and Schaft Syst.

Machine Code	Component Code	Component Type	P.M. Material & Labour Costs C_p	P.M. Downtime Cost V	F.M. Material & Labour Costs C_f	F.M. Down-time Cost U	F.M. Down-time Days d	F.M. Daily Downtime Cost K	Name of Component or Subsystem
13 FR 9	018	A	3.000	-	6.000	13.000	-	-	Vee-Belt
14 DECCO	002	A	5.000	-	5.000	30.000	-	-	Oil Filter
	003	B	11.000	30.000	14.000	90.000	-	-	Emulsion Pump
	017	B	16.000	60.000	16.000	120.000	-	-	Turkshead
	018	A	4.000	-	10.000	15.000	-	-	Vee-Belt
17 U 171	001	A	4.000	-	4.000	30.000	-	-	Drawing Head and Capstan
	002	A	3.000	-	6.000	30.000	-	-	Oil Filter
	003	B	6.000	30.000	8.000	90.000	-	-	Emulsion Pump
	006	D	40.000	600.000	70.000	-	1.3	720.000	Geous, Pinions and Schafts Syst
	008	B	5.000	30.000	5.000	90.000	-	-	Wire Induction Bridge
	009	A	2.000	-	2.000	15.000	-	-	Air Ventils and Channels
	018	A	4.000	-	8.000	15.000	-	-	Vee-Belt
18 U 172	001	A	4.000	-	4.000	30.000	-	-	Drawing Head and Capstan
	002	A	3.000	-	6.000	30.000	-	-	Oil Filter
	003	B	6.000	30.000	8.000	90.000	-	-	Emulsion Pump

Machine Code	Component Code	Component Type	P.M. Material & Labour Costs C_p	P.M. Downtime Cost V	F.M. Material & Labour Costs C_f	F.M. Down-time Cost U	F.M. Down-time Days d	F.M. Daily Downtime Cost K	Name of Component or Subsystem
18 U 172	006	D	40.000	600.000	70.000	-	1.3	720.000	Gears, Pinions and Schafts Syst
	008	B	5.000	30.000	5.000	90.000	-	-	Wire Induction Bridge
	009	A	2.000	-	2.000	15.000	-	-	Air Ventils and Channels
	018	A	4.000	-	8.000	15.000	-	-	Vee-Belt
19 NIE 1	001	A	5.000	-	5.000	25.000	-	-	Drawing Head and Capstans
	002	A	3.000	-	5.000	25.000	-	-	Oil Filters
	006	D	55.000	500.000	80.000	-	1.2	600.000	Geart Pinions and Schaft
	008	B	4.000	25.000	4.000	75.000	-	-	Wire Induction Bridges
	009	A	2.000	-	2.000	13.000	-	-	Air Ventils and Channels
	018	A	5.000	-	10.000	13.000	-	-	Vee-Belts
20 NIE 2	001	A	5.000	-	5.000	25.000	-	-	Drawing Head and Capstans
	002	A	3.000	-	5.000	25.000	-	-	Oil Filters
	006	D	55.000	500.000	80.000	-	1.2	600.000	Gears, Pinions and Schafts

Machine Code	Component Code	Component Type	P.M. Material & Labour Costs C_p	P.M. Downtime Cost V	F.M. Material & Labour Costs C_f	F.M.Down-time Cost U	F.M.Down-time Days d	F.M.Daily Downtime Cost K	Name of Component or Subsystem
20 NIE 2	008	B	4.000	25.000	4.000	75.000	-	-	Wire Induction Bridges
	009	A	2.000	-	2.000	13.000	-	-	Air Ventils and Channels
	018	A	5.000	-	10.000	13.000	-	-	Vee-Belt
21 W2 12	001	A	5.000	-	6.000	35.000	-	-	Drawing Head and Capstan
	002	A	3.000	-	3.000	35.000	-	-	Oil Filters
	008	B	6.000	35.000	8.000	105.000	-	-	Wire Induction Bridges
	011	B	10.000	35.000	15.000	70.000	-	-	Variator
	013	A	5.000	-	7.000	35.000	-	-	Spooling System
	018	A	4.000	-	8.000	18.000	-	-	Vee-Belt
21 W2 11	001	A	4.500	-	5.000	35.000	-	-	Drawing Head and Capstan
	002	A	3.000	-	3.000	35.000	-	-	Oil Filters
	008	B	6.000	35.000	7.000	105.000	-	-	Wire Induction Bridges
	011	B	9.000	35.000	15.000	70.000	-	-	Var iator
	013	A	5.000	-	7.000	35.000	-	-	Spooling System
	018	A	4.000	-	8.000	18.000	-	-	Vee-Belt

APPENDIX - III

OUTPUT-DATA SUMMARY FOR FIRST PHASE SOLUTIONS

SUMMARY OF OUTPUT-DATA FOR FIRST-PHASE SOLUTIONS

Mach./Component	Lifetime Model Selected	Parameter Estimates Of Lifetime Model				Q-Statistic	D_n-Statistic	Optimal Planned Replacement Periods (Days)	Minimum Expected Daily Cost Of P.R. Policy (TL.)	Reliabilities At Optimal P.R.Periods	Total Expected Replacement Cycles/ Annum
		β	λ	σ	μ						
1KATEL/001	WEIBULL	3.2	12.6			1.191	-	6	1572,5	0.91	48.1
005	WEIBULL	3.0	26.6			0.895	-	16	658,5	0.80	18.5
006	WEIBULL	3.3	10.1			0.529	-	9	65791,7	0.51	33.7
013	WEIBULL	2.6	15.3			0.534	-	10	1641,8	0.72	31.1
015	WEIBULL	2.2	18.9			0.759	-	13	25036,9	0.64	24.0
016	WEIBULL	2.3	23.2			0.563	-	16	934,0	0.66	19.9
018	WEIBULL	2.8	38			0.869	-	22	289,7	0.81	13.5
2KATEL/001	WEIBULL	1.8	12.8			1.34	-	5	3134,3	0.83	61.0
005	WEIBULL	3.8	24			0.378	-	13	619,8	0.91	22.1
006	WEIBULL	2.8	16.1			0.577	-	15	59577	0.44	21.6
013	WEIBULL	3.2	25.7			0.702	-	15	819,1	0.83	19.6
015	WEIBULL	3.9	25.6			0.666	-	16	18718,5	0.85	17.9
016	WEIBULL	3.3	27.4			0.709	-	15	591,1	0.87	19.3
018	WEIBULL	3.5	36.9			0.416	-	19	227,3	0.91	15.1

SUMMARY OF OUTPUT-DATA FOR FIRST-PHASE SOLUTIONS

Mach./Component	Lifetime Model Selected	Parameter Estimates Of Lifetime Model				Q-Statistic	D_n-Statistic	Optimal Planned Replacement Periods (Days)	Minimum Expected Daily Cost Of P.R. Policy (TL.)	Reliabilities At Optimal P.R.Periods	Total Expected Replacement Cycles/ Annum
		β	λ	σ	μ						
3KATEL/001	WEIBULL	2.6	14.8			1.08	-	5	1625,0	0.94	57.3
005	LOGNORMAL	5.1	-	6.9	26.2	-	0.21	13	499,4	0.94	21.8
006	LOGNORMAL	4.6	-	5.7	20.7	-	0.18	9	19672,0	0.96	31.2
013	WEIBULL	3.6	21.2			0.246	-	10	805,0	0.93	28.5
015	LOGNORMAL	5.4		5.7	28.4	-	0.15	15	16821,3	0.94	18.8
016	LOGNORMAL	4.0		9.2	34.4	-	0.15	15	463,0	0.93	19.0
018	WEIBULL	3.5	36.8			0.416		18	238,6	0.92	15.9
80RME1/002	WEIBULL	3.6	32.3			0.408		15	288,9	0.94	18.9
006	WEIBULL	2.6	16.5			0.936		21	45729,9	0.15	18.8
012	WEIBULL	3.3	26.9			0.832		14	523,7	0.89	20.6
013	WEIBULL	2.7	26.5			0.769		11	565,2	0.91	26.2
014	WEIBULL	3.3	26.3			0.318		14	305,8	0.88	20.7
018	WEIBULL	3.1	35.4			0.327		13	117,9	0.96	21.8

SUMMARY OF OUTPUT-DATA FOR FIRST-PHASE SOLUTIONS

Mach./Component	Lifetime Model Selected	Parameter Estimates Of Lifetime Model				Q-Statistic	D_n-Statistic	Optimal Planned Replacement Periods (Days)	Minimum Expected Daily Cost Of P.R. Policy (TL.)	Reliabilities At Optimal P.R. Periods	Total Expected Replacement Cycles/ Annum
		β	λ	σ	μ						
90RME2/002	WEIBULL	3.9	36.3			0.327		13	316,7	0.95	16.7
006	WEIBULL	2.5	20.8			0.365		25	47698,7	0.20	15.4
012	WEIBULL	3.3	29.5			0.428		14	519,2	0.92	20.5
013	WEIBULL	3.0	24.1			0.548		10	613,3	0.93	28.6
014	WEIBULL	2.3	19.0			0.544		9	592,9	0.84	33.1
018	WEIBULL	3.2	40.6			0.461		14	105,2	0.97	20.2
100RME3/002	LOGNORMAL	4.9		7.4	34.0		0.150	16	401,2	0.95	17.7
006	WEIBULL	2.1	10.6			3.29		16	104544,9	0.10	27.9
012	WEIBULL	3.7	22.6			1.71		11	634,2	0.93	25.9
013	WEIBULL	3.2	22.8			4.88		10	731,0	0.93	28.6
014	WEIBULL	1.8	23.8			6.82		14	706,3	0.68	23.2
018	WEIBULL	2.6	30.5			0.442		11	288,6	0.93	26.1
12FS13/001	WEIBULL	2.7	6.7			0.495		2	3227,5	0.96	143.2

SUMMARY OF OUTPUT-DATA FOR FIRST-PHASE SOLUTIONS

Mach./Component	Lifetime Model Selected	Parameter Estimates Of Lifetime Model				Q-Statistic	D_n-Statistic	Optimal Planned Replacement Periods (Days)	Minimum Expected Daily Cost Of P.R. Policy (TL.)	Reliabilities At Optimal P.R.Periods	Total Expected Replacement Cycles/ Annum
		β	λ	σ	μ						
002	WEIBULL	2.3	8.7			1.26		4	2945,6	0.85	75.3
003	WEIBULL	2.8	15.5			0.677		11	5813,6	0.68	28.5
006	WEIBULL	2.2	19.0			0.586		22	67680,0	0.25	17.3
007	LOG NORMAL	4.4		7.1	27.3		0.16	6	1698,2	0.99	46.7
018	WEIBULL	2.6	33.2			0.457		12	270,7	0.93	23.8
13FR9/001	WEIBULL	1.4	6.8			0.606		3	7445,1	0.73	112.1
002	WEIBULL	2.0	6.8			0.406		2	3480,9	0.91	148.1
003	WEIBULL	2.3	11.5			0.412		8	7472,1	0.65	40.7
004	WEIBULL	1.4	7.6			1.403		22	17320,4	0.02	43.6
005	LOGNORMAL	7.5		4.5	26.3		0.28	15	450,1	0.97	18.8
006	EXPONENT.	~1.0				NO	PLANNED	-REPLACEMENT	APPLICABLE		
018	WEIBULL	2.6	32.9			0.361		14	343,0	0.90	20.7
3											

SUMMARY OF OUTPUT-DATA FOR FIRST-PHASE SOLUTIONS

Mach./Component	Lifetime Model Selected	Parameter Estimates Of Lifetime Model				Q-Statistic	D_n-Statistic	Optimal Planned Replacement Periods (Days)	Minimum Expected Daily Cost Of P.R. Policy (TL.)	Reliabilities At Optimal P.R. Periods	Total Expected Replacement Cycles/Annum
		β	λ	σ	μ						
14DECCO/002	LOGNORMAL	5.6		3.9	19.8		0.26	10	635,4	0.96	28.3
003	WEIBULL	2.3	17.5			1.15		13	5912,9	0.61	25.2
017	WEIBULL	2.3	10.1			1.99		10	15321,3	0.37	37.8
018	WEIBULL	3.4	40.5			0.611		19	296,6	0.93	15.0
17U171/001	WEIBULL	1.5	6.2			0.514		3	5061,1	0.71	112.7
002	LOGNORMAL	4.3	24.9				0.19	11	366,0	0.97	25.6
003	LOGNORMAL	7.0	28.8				0.21	21	2059,4	0.89	13.6
006	WEIBULL	3.4	20.3			0.982		8	17162,2	0.96	35.2
008	WEIBULL	3.7	21.1			4.85		14	3509,8	0.81	21.1
009	WEIBULL	2.8	25.9			0.436		10	304,3	0.93	28.6
018	WEIBULL	2.7	32.4			0.444		15	436,0	0.88	19.4
18U172/001	-	0.7		D.F.R. NO PLANNED-REPLACEMENT APPLICABLE							
002	LOGNORMAL	9.1					0.17	16	208,9	0.99	17.5

SUMMARY OF OUTPUT-DATA FOR FIRST-PHASE SOLUTIONS

Mach./Component	Lifetime Model Selected	Parameter Estimates Of Lifetime Model				Q-Statistic	D_n-Statistic	Optimal Planned Replacement Periods (Days)	Minimum Expected Daily Cost Of P.R. Policy (TL.)	Reliabilities At Optimal P.R.Periods	Total Expected Replacement Cycles/ Annum
		β	λ	σ	μ						
18U172/003	WEIBULL	3.5	23.7			0.753		16	3321,9	0.77	18.6
006	WEIBULL	1.8	9.9			0.451		25	105077,8	0.01	29.3
008	WEIBULL	2.9	24.5			1.97		16	3412,6	0.74	19.0
009	LOGNORMAL	7.2		7.3	45.8		0.21	25	94,7	0.98	11.2
018	WEIBULL	3.1	35.2			0.574		17	353,0	0.90	16.9
19NIE1/001	WEIBULL	2.9	9.7			0.398		4	1777,8	0.92	72.2
002	LOGNORMAL	6.0		5.6	29.4		0.16	14	259,3	0.98	20.1
006	WEIBULL	3.8	24.1			1.500	0.19	24	34352,4	0.37	13.6
008	LOGNORMAL	5.0		7.5	27.7		0.26	16	2274,5	0.87	18.0
009	WEIBULL	3.8	27.6			0.317		13	214,0	0.94	21.9
018	WEIBULL	3.3	38.9			0.573		20	358,1	0.89	14.4
20NIE2/001	WEIBULL	2.7	14.5			0.672		7	1233,0	0.87	41.9
002	LOGNORMAL	4.0		9.7	32.5		0.13	12	340,5	0.96	23.6

SUMMARY OF OUTPUT-DATA FOR FIRST-PHASE SOLUTIONS

Mach./Component	Lifetime Model Selected	Parameter Estimates Of Lifetime Model				Q-Statistic	D_n-Statistic	Optimal Planned Replacement Periods (Days)	Minimum Expected Daily Cost Of P.R. Policy (TL.)	Reliabilities At Optimal P.R.Periods	Total Expected Replacement Cycles/ Annum
		β	λ	σ	μ						
20NIE2/006	WEIBULL	3.7	27.6			1.719		28	30229,8	0.35	11.9
008	LOGNORMAL	4.2		11.2	36.8		0.23	20	1888,1	0.85	14.5
009	LOGNORMAL	4.7		9.4	33.9		0.21	15	172,1	0.96	18.8
018	WEIBULL	3.1	35.2			0.414		18	408,8	0.88	16.1
21W211/001	WEIBULL	2.3	10.3			0.376		4	2145,1	0.90	73.4
002	LOGNORMAL	7.7		4.2	28.1		0.16	15	235,4	0.99	18.7
008	LOGNORMAL	6.0		5.1	24.8		0.24	15	3240,2	0.90	19.0
011	WEIBULL	2.4	14.5			0.444		13	6380,0	0.46	27.0
013	LOGNORMAL	5.0		10.2	47.8		0.13	21	297,9	0.97	13.4
018	WEIBULL	2.9	31.4			0.467		14	437,6	0.91	20.5
21W212/001	WEIBULL	2.8	12.3			0.515		5	1622,0	0.92	57.7
002	LOGNORMAL	5.9		5.9	29.5		0.12	13	273,9	0.98	21.6
008	LOGNORMAL	6.6		4.7	24.2		0.25	15	3167.9	0.92	18.9

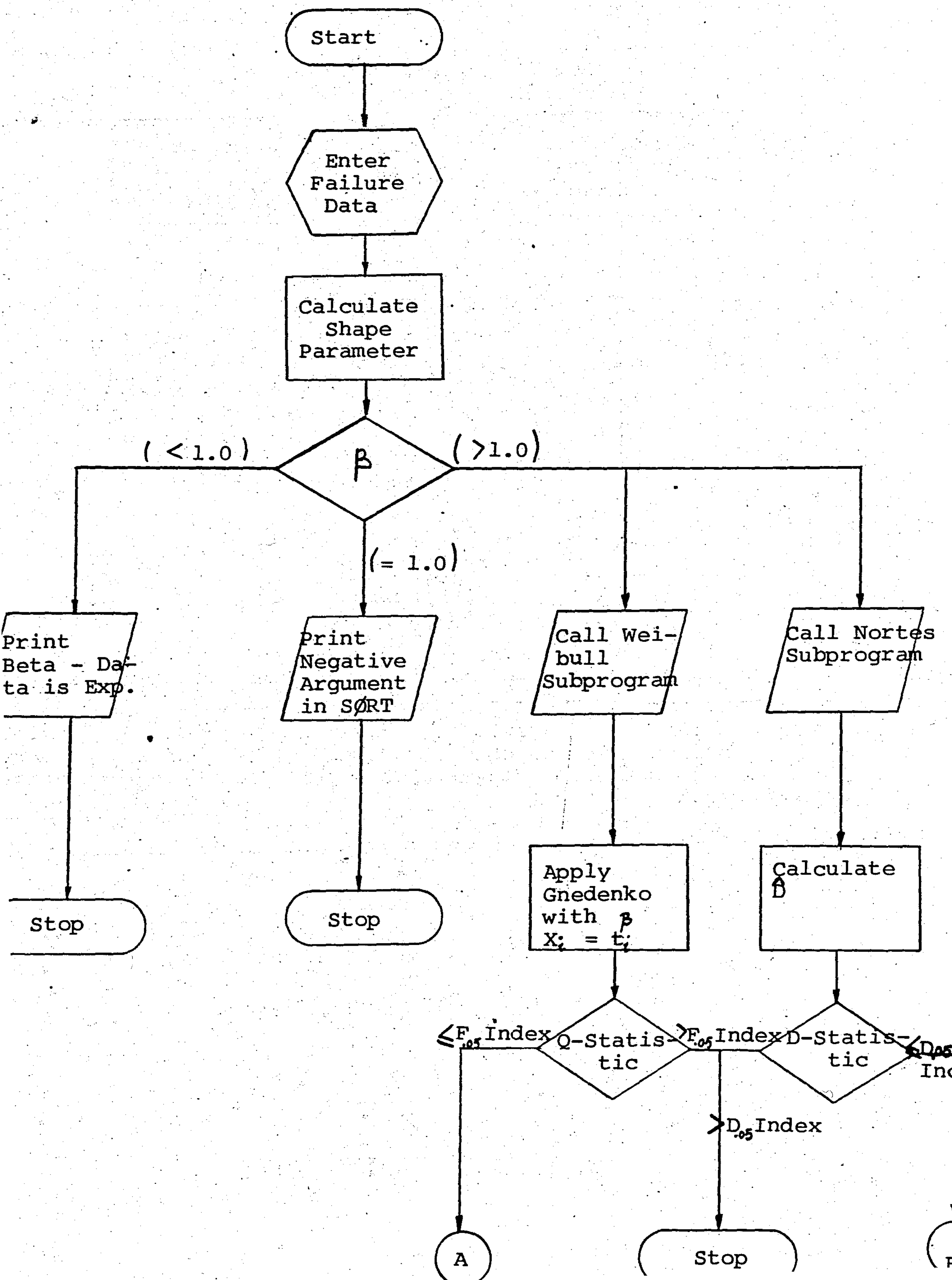
SUMMARY OF OUTPUT-DATA FOR FIRST-PHASE SOLUTIONS

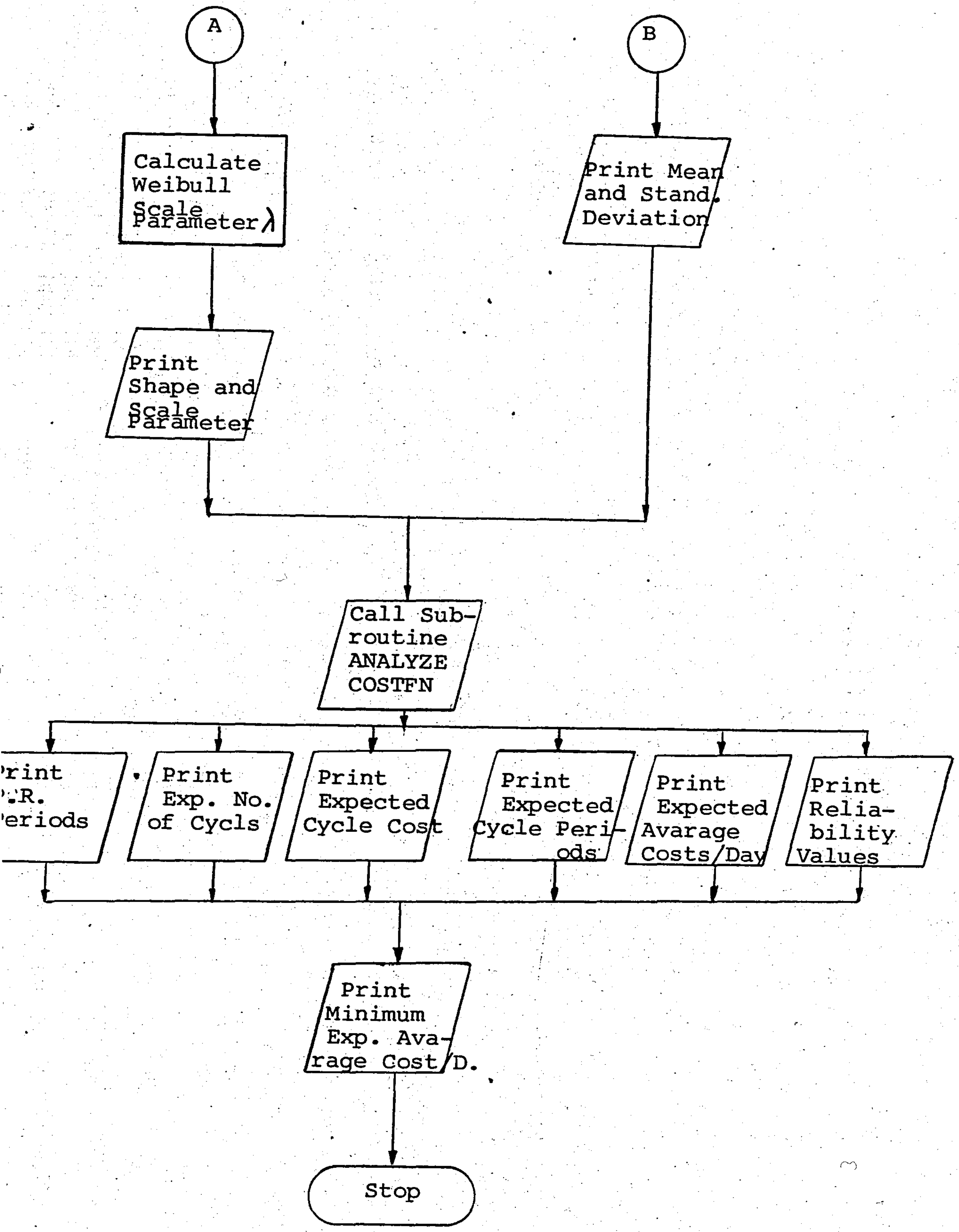
Mach./Component	Lifetime Model Selected	Parameter Estimates Of Lifetime Model				Q-Statistic	D_n-Statistic	Optimal Planned Replacement Periods (Days)	Minimum Expected Daily Cost Of P.R. Policy (TL.)	Reliabilities At Optimal P.R.Periods	Total Expected Replacement Cycles/ Annum
		β	λ	σ	μ						
21W212/011	WEIBULL	3.6	13.1			0.419		10	6358,5	0.68	30.8
013	LOGNORMAL	4.0		11.5	44.9		0.26	17	384,8	0.96	16.6
018	WEIBULL	2.6	31.0			0.415		13	490,9	0.90	22.3
11HKW9/001	WEIBULL	2.6	8.9			0.954		3	2404,6	0.94	96.1
003	WEIBULL	3.9	9.3			0.306		6	7317,8	0.83	49.2
004	WEIBULL	2.9	7.4			0.321		6	15732,6	0.58	55.1
006	WEIBULL	2.1	9.0			3.07		14	103825,4	0.07	32.6
018	WEIBULL	2.5	25.1			0.355		12	957,8	0.86	24.5

APPENDIX - IV

DATA-PROCESSING

FLOW-CHART FOR STATISTICAL ANALYSIS OF FAILURE DATA AND COST CALCULATIONS




A
B
Calculate Weibull Scale Parameter λ
Print Mean and Stand. Deviation
Print Shape and Scale Parameter
Call Subroutine ANALYZE COSTFN
Print P.R. Periods
Print Exp. No. of Cycls
Print Expected Cycle Cost
Print Expected Cycle Periods
Print Expected Avarage Costs/Day
Print Reliability Values
Print Minimum Exp. Avarage Cost/D.
Stop

OUTPUT- A

```
TTTTTTTTTTTT      AAAAAAAAAA      NNN       NN      AAAAAAAAAA
     TT          AA        AA     NNNN      NN     AA        AA
     TT          AA        AA     NNNNN     NN     AA        AA
     TT          AA        AA     NN NNN    NN     AA        AA
     TT          AAAAAAAAAAAA     NN  NNN   NN     AAAAAAAAAAAA
     TT          AAAAAAAAAAAA     NN   NNN  NN     AAAAAAAAAAAA
     TT          AA        AA     NN    NNN NN     AA        AA
     TT          AA        AA     NN     NNNNN     AA        AA
     TT          AA        AA     NN      NNNN     AA        AA
     TT          AA        AA     NN       NNN     AA        AA
     TT          AA        AA     NN        NN     AA        AA
* * * UNIVAC 1106 -- BOGAZICI UNIVERSITESI KOMPUTER MERKEZI --ISTANBUL VER. 33R3/BU9-7  SITE

   RUNID * TANA          USER ID *             PART NUMBER * 00     INPUT DEVICE * SC6T01

     FILE NAME * PRΔ000TANA            CREATED AT:  09:43:41 JUN 23,1981          PRINTED AT:

12345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
ΔRUN,E/BR TAN,111-15-219,TAN,5,250
ΔASG,A LINPAK*LINPAK/
FAC WARNING       040200000000
ΔASG,A BU*BULIB.
FAC WARNING       040000000200
ΔFTN,IS  .MAIN
FTN 8R1  *06/23/81-09:43(,0)
          EXTERNAL  FX
          PARAMETER  L=50
          INTEGER  V1,V2
          CHARACTER*12  KOD,KOD1
          DIMENSION T(L),X(L),Y(L),NTY(4)
          DATA (NTY(I),I=1,4)/,A,,,B,,,C,,,D,/
          EXL=0.95
          ITYPE=1
          CP=1000.0
          CKI1=20000.0
          CKI2=0.0
          CF=1000.0
        1 READ(5,101)KOD,N,(T(I),I=1,13)
      101 FORMAT(A12,I3,13(F5.0))
          IF(N.LE.13)GO TO 2
          READ(5,102)(T(I),I=14,N)
      102 FORMAT(16F5.0)
        2 READ(5,103)KOD1,ITYPE,CP,VI,CF,CKI1,DI,CKI2
```

```
  103 FORMAT(A12,2X,I1,6F10.0)
      IF(KOD1.NE.KOD)PRINT*,, KOD ERROR,,KOD,KOD1
      CALL MENNON(T,N,BETA,IER)
      CALL EXPTES(T,N,X,Y,AX,A,B,R,ALFA,BETA)
C
C     MACHINE SUMMARY OUTPUT SECTION
C
      WRITE(6,201)KOD,NTY(ITYPE),N,BETA,ALFA
  201 FORMAT(1H1,//,10X,,MACHINE / COMPONENT  ,,A12,,    TYPE OF COMPONE
     *NT  ,,A1,/,10X,,NUMBER OF OBSERVATIONS,,I3,/,10X,,SHAPE PARAMETER,
     *,F10.5,/,10X,,SCALE PARAMETER,,F10.5)
      WRITE(6,202)CP,VI,CF,CKI1,DI,CKI2
  202 FORMAT(///,10X,,COST COEFFICIENTS,,/,10X,17(1H*),/,10X,
     *,P.M MATERIAL & LABOUR COST,,T40,F10.2,, TL.,,/,10X,,P.M DOWNTIME
     *COST,,T40,F10.2,, TL.,,/,10X,,F.M MATERIAL & LABOUR COST,,T40,F10.
     *2,, TL.,,/,10X,,F.M DOWN TIME COST,,T40,F10.2,, TL.,,/,10X,
     *,F.M DOWN TIME DAYS,,T40,F6.2,/,10X,,F.M DAILY DOWNTIME COST,,
     *T40,F10.2,, TL.,)
```

```
      IF(IER.EQ.1)GO TO 91
      IF(BETA.GE.EXL)GO TO 10
      PRINT *,KOD,,BETA IS LESS THAN EXL,BETA=,,BETA
      GO TO 99
   10 CONTINUE
C     FIND THE INTERVAL AND TYPE OF DISTRIBUTION
      IF(BETA.GE.EXL.AND.BETA.LE.1.0)GO TO 40
      IF(BETA.GT.1.0.AND.BETA.LT.4.0)GO TO 50
   60 CONTINUE
C     NORMAL  DISTRIBUTION
      CALL NORTES(FX,T,N,DMAX,TBAR,SDEV)
      GO TO 99
   50 CONTINUE
C     WEIBULL  DISTRIBUTION
      CALL WEIBUL(T,N,BETA,X,V1,V2,Q)
      ALP=0.9
      F1=FISHIN(ALP,V1,V2,$51)
   51 ALP=0.1
      F2=FISHIN(ALP,V1,V2,$52)
   52 CONTINUE
      WRITE(6,203)F2
  203 FORMAT(/,10X,,FISHER TEST CRITICAL VALUE,,F12.6)
      IF (BETA.GT.3.0)GO TO 60
      GO TO 99
   40 CONTINUE
C     EXPONENTIAL DISTRIBUTION
      GO TO 99
   91 PRINT *,KOD,,NEGATIVE ARGUMENT IN SQRT,
   99 CONTINUE
      CALL ANLYZE(BETA,ALFA,ITYPE,CP,CF,DI,CKI1,CKI2,VI,N,KOD,T)
      GO TO 1
  999 STOP
      END
```

```
END FTN 100 IBANK 513 DBANK
ΔFTN,IS  .MENNON
FTN 8R1  *06/23/81-09:44(,0)
            SUBROUTINE MENNON(T,N,BETA,IER)
            DIMENSION  T(N)
            IER=0
            BETA,U,V=0.0
            DO 10 I=1,N
1           AD=ALOG(T(I))
1           U=U+AD
1           V=V+AD*AD
1        10 CONTINUE
            AD=(V-U*U/N)*0.609
            IF(AD.LT.0.0)GO TO 20
            AD=SQRT(AD/(N-1))
            BETA=1./AD
            RETURN
         20 IER=1
            RETURN
            END
END FTN 72 IBANK 22 DBANK
ΔFTN,IS  .NORTES
FTN 8R1  *06/23/81-09:44(,0)
            SUBROUTINE  NORTES(FX,T,N,DMAX,TBAR,SDEV)
            EXTERNAL  FX
            DIMENSION T(N)
            SN=N
            CALL MEAN(T,N,TBAR)
            CALL STDEV(T,TBAR,N,SDEV)
            DMAX=-1.E10
            A1=-6.0
            DO 10 I=1,N
1           S=I-1
1           Z=(T(I)-TBAR)/SDEV
1           M=(Z-A1)/0.07
```

```
1              F2=(S+1)/SN-F
1              DEL=AMAX1(F1,F2)
1              IF(DEL.GT.DMAX)DMAX=DEL
1           10 CONTINUE
               WRITE(6,101)TBAR,SDEV,DMAX
           101 FORMAT(/,20X,,NORMALITY TEST,,2X,, MEAN,,G12.5,,  ST.DEV ,,G12.5,
              *,  MAXIMUM D-VALUE,,G14.6)
            20 RETURN
               END

END FTN 105 IBANK 80 DBANK
ΔFTN,IS  .MEAN
FTN 8R1  *06/23/81-09:44(,0)
               SUBROUTINE  MEAN(X,N,A)
               DIMENSION  X(N)
               S=0.0
               DO 10 I=1,N
1              S=S+X(I)
1           10 CONTINUE
               A=S/N
               RETURN
               END

END FTN 38 IBANK 13 DBANK
ΔFTN,IS  .STDEV
FTN 8R1  *06/23/81-09:44(,0)
               SUBROUTINE  STDEV(X,A,N,SD)
               DIMENSION X(N)
               S=0.0
               DO 10 I=1,N
1              S=S+(X(I)-A)**2
1           10 CONTINUE
               SD=SQRT(S/N)
               RETURN
               END

END FTN 47 IBANK 20 DBANK
ΔFTN,IS .WEIBUL
FTN 8R1  *06/23/81-09:44(,0)
               SUBROUTINE WEIBUL (T,N,BETA,X,V1,V2,Q)
               INTEGER  V1,V2
               DIMENSION T(N),X(N)
          C
```

```
      S1 = N*(T(1)**BETA)
      DO 10 I = 1,N
   10 X(I) = T(I)**BETA



      L = (N+1) / 2
      DO 20 I = 2,L
      S1 = S1 + (N-I+1) * (X(I) - X(I-1) )
   20 CONTINUE
      L1 = L + 1
      DO 30 I = L1,N
      S2 = S2 + (N-I+1) * (X(I) - X(I-1) )
   30 CONTINUE
      S1 = S1 / L
      S2 = S2 / (N-L)
      V1=L
      V2=N-L
      Q = S1/S2
      WRITE(6,101)V1,V2,Q
  101 FORMAT(/,20X,,GNEDENKO TEST,,4X,,  DEGREE OF FREEDOM(1),,I3
     *,5X,,DEGREE OF FREEDOM(2),,I3,/,20X,,  Q - VALUE,,F12.8)
      RETURN
      END

END FTN 143 IBANK 71 DBANK
ΔFTN,IS  .EXPTES
FTN 8R1  *06/23/81-09:44(,0)
      SUBROUTINE  EXPTES(T,N,X,Y,AX,A,B,R,ALFA,BETA)
      DIMENSION  T(N),X(N),Y(N)
C     T(I) : ORDERED
C     AX: X INTERCEPT
C     A: Y INTERCEPT
C     B: SLOPE
C     ALFA: PARAMETER OF EXP DISTRIBUTION
      SUM=0.0
      DO 20 I=1,N
      X(I)=ALOG(T(I))
   20 SUM=SUM+X(I)
      ST=SUM/N
      ST=ST-0.577*(1./BETA)
```

```
      ALFA=EXP(ST)
      RETURN
      END

END FTN 75 IBANK 31 DBANK
@FTN,IS  .ANLYZE
FTN 8R1  *06/23/81-09:45(,0)
      SUBROUTINE ANLYZE(BETA,ALFA,ITYPE,CP,CF,DI,CKI1,CKI2,VI,N,KOD,T)
      CHARACTER*12  KOD
      DIMENSION T(N),X(100),Y(100)
      IJK=1
      IF(BETA.GE.1.0.AND.BETA.LE.4.0)IJK=1
      CMIN=9.E18
      LIMIT=T(N)+1
      RSUM=0.0
      WRITE(6,101)KOD
  101 FORMAT(/,2X,,T(I),,4X,,MACHINE / COMPONENT,,2X,A12,/,5X,,NO . OF C
     *YCLES,,5X,,EXPECTED CYCLE COST (TL),,5X,,EXPECTED CYCLE TIME (DAYS
     *),,5X,,EXPECTED AVG COST/DAY,,3X,,R(T(I)),,/,5X,14(1H*),5X,24(1H*)
     *,5X,26(1H*),5X,21(1H*),3X,8(1H*)/)
      DO 10 I=1,LIMIT
      J=I
      X(I)=J
      R=REL(BETA,ALFA,IJK,J)
      CALL COSTFN(CP,CF,DI,CKI1,CKI2,VI,RSUM,R,COST,ITYPE,ECC,ECT)
      Y(I)=COST
      AOC=280/ECT
      WRITE(6,102)J,AOC,ECC,ECT,COST,R
  102 FORMAT(1X,I3,5X,F6.2,15X,F12.2,21X,F6.2,20X,F12.2,7X,F8.6)
C     PRINT INTERMEDIATE RESULTS
      IF(COST.LT.CMIN)CMIN=COST
   10 CONTINUE
      WRITE(6,103)CMIN
  103 FORMAT(//,10X,,MINIMUM AVERAGE COST/DAY ,,F12.2,, TL.,)
      IF(LIMIT.GE.1)GO TO 20
      CALL GRAPH4(8.0,8.0,LIMIT,X,Y)
   20 RETURN
      END
```

```
      SUBROUTINE COSTFN(CP,CF,DI,CKI1,CKI2,VI,RSUM,R,COST,ITYPE,ECC,ECT)
      RSUM=RSUM+R
      GO TO (10,20,30,40),ITYPE
   10 B=CKI1+CF
      ECC=CP*R+B*(1.0-R)
      ECT=RSUM
      COST=ECC/ECT
      RETURN
   20 B=VI+CP
      C=CKI1+CF
      ECC=B*R+C*(1.0-R)
      ECT=RSUM
      COST=ECC/ECT
      RETURN
   30 B=CKI2*DI+CF
      C=DI*(1.0-R)
      ECC=CP*R+B*(1.0-R)
      ECT=RSUM+C
      COST=ECC/ECT
      RETURN
   40 B=VI+CP
      C=DI*CKI2+CF
      D=DI*(1.0-R)
      ECC=B*R+C*(1.0-R)
      ECT=RSUM+D
      COST=ECC/ECT
      RETURN
      END

END FTN 95 IBANK 12 DBANK
ΔFTN,IS .REL
FTN 8R1   *06/23/81-09:45(,0)
      FUNCTION REL(BETA,ALFA,IJK,J)
      GO TO (10,20),IJK
   10 B=J/ALFA
      C=1.0
      IF(B.EQ.0.0)GO TO 11
      B=B**BETA
      C=EXP(B)
      C=1.0/C
   11 REL=C
      RETURN
   20 CONTINUE
```

```
                REL=1.0
                RETURN
                END

END FTN 40 IBANK 13 DBANK
ΔFTN,IS  .FX
FTN 8R1  *06/23/81-09:45(,0)
                FUNCTION  FX(X)
                FX=(1./SQRT(2*3.14159))*EXP(-X*X/2.)
                RETURN
                END

END FTN 24 IBANK 14 DBANK
ΔMAP,I  ,.MAIN
MAP 30R1 S74T11 06/23/81 09:45:21


ADDRESS LIMITS      001000 005677       2496 IBANK WORDS DECIMAL
                    040000 047150       3689 DBANK WORDS DECIMAL
STARTING ADDRESS    005534



              SEGMENT $MAIN$               001000 005677      040000 047150

ASINCOS$/MATH               $(1)     001000 001215     $(2)      040000 040027
                            $(037)   INFO-010-LC       $(034)    MOERO$
MBPKT$                                                 $(2)      040030 040041

ASINCOS$/MATH               $(1)     001000 001215     $(2)      040000 040027
                            $(037)   INFO-010-LC       $(034)    MOERO$
MBPKT$                                                 $(2)      040030 040041
F2RTRN$                                                $(2)      040042 040043
OVERFL$/FORFTN              $(1)     001216 001246
CHOPN                                                  $(4)      040044 040246
F2TABX                                                 $(2)      040247 040560
F2FCA                                                  $(0)      040561 040565
FORCOM$/FORFTN                                         $(2)      040566 040573
F2CLOSE                     $(1)     001247 001300     $(0)      040574 040576
CLRU$
PMD$COM(COMMONBLOCK)                                             040577 040577
F2CON                                                  $(2)      040600 042454
                                                       $(034)    MOERO$
```

F2INIT			$(2)	043047 043226
F2ACTIV$/FORFTN	$(1)	001404 001417	$(2)	043227 043231
	$(3)	001420 001433		
	$(5)	001434 001434		
CHACT			$(0)	043232 043270
CHCNE			$(0)	043271 043415
EXP$/MATH	$(1)	001435 001525	$(2)	043416 043437
	$(037)	INFO-010-LC	$(034)	MOERO$
SQRT$/MATH	$(1)	001526 001567	$(2)	043440 043452
	$(037)	INFO-010-LC	$(034)	MOERO$
F2CDCD$			$(2)	043453 043520
XPRR$/MATH	$(1)	001570 001774	$(2)	043521 043575
	$(037)	INFO-010-LC	$(034)	MOERO$
XPRI$/MATH	$(1)	001775 002061	$(2)	043576 043603
	$(037)	INFO-010-LC	$(034)	MOERO$
ERU$/SYS74R1				
F2EXIT			$(2)	043604 043637
F2IOENT				
MOERO$(COMMONBLOCK)				043640 043643
ALOG$/MATH	$(1)	002062 002205	$(2)	043644 043712
	$(037)	INFO-010-LC	$(034)	MOERO$
FISH	$(1)	002206 002535	$(0)	043713 043722
			$(4)	043723 043737
			$(6)	043740 043752
			$(012)	043753 043755
			$(012)	044753 044755
REL	$(1)	004162 004231	$(0)	044756 044757
			$(4)	044760 044764
			$(6)	044765 044771
			$(012)	044772 044772
COSTFN	$(1)	004232 004370	$(0)	044773 044775
3			$(4)	044776 045004
			$(6)	045005 045005
			$(012)	045006 045006
ANLYZE	$(1)	004371 004573	$(0)	045007 045331
			$(4)	045332 045533
			$(6)	045534 045564
			$(012)	045565 045572
EXPTES	$(1)	004574 004706	$(0)	045573 045575

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V I T A

The author was born in 1946, in Foça-İzmir. After completion of Lyceum in 1965, he entered Robert College School of Business Administration and Economics. He received the degree of Bachelor of B.A. in Industrial Management in 1969 and the Master of Industrial Management in 1971. His work experiences in the private sector are as follows;

He was employed as assistant in the Organization and IBM Departments of Turk-Hoechst A.S. between 1971 Oct.-1972 Nov. Later, between 1972 Nov.-1973 April, he worked as the Financial and Executive Director of the Turkish Airlines Foundation. After execution of military service in Turkish Air Forces, he entered Rabak A.S. in Oct.-1974 and worked in the Export and Marketing Divisions and later in the Project and Development Department of this company. In Sept. 1975, he went to Sweden and participated in a Seminar related to "Industrial Relations" in Stockholm. In 1979, he undertook the Industrial Engineering Master's Program in Boğaziçi University. He took the position of supply manager in Çukur-ova Import and Export Co. in 1980 June. He has numerous publishings related to operational research applications in industry and a book related to "Swedish Unionism and Collective Bargaining System" published in Jan. 1976. Currently, he is a member of the Turkish Operational Research Society and the American Institute of Industrial Engineering. He is married to Dr.Nükhet Tan.