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MAINTAINABILITY

by

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Denmark

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its mission; if they are exceeded, it will not. An example is shown in Figure 1, where the dotted line shows the minimum number of ready missiles.

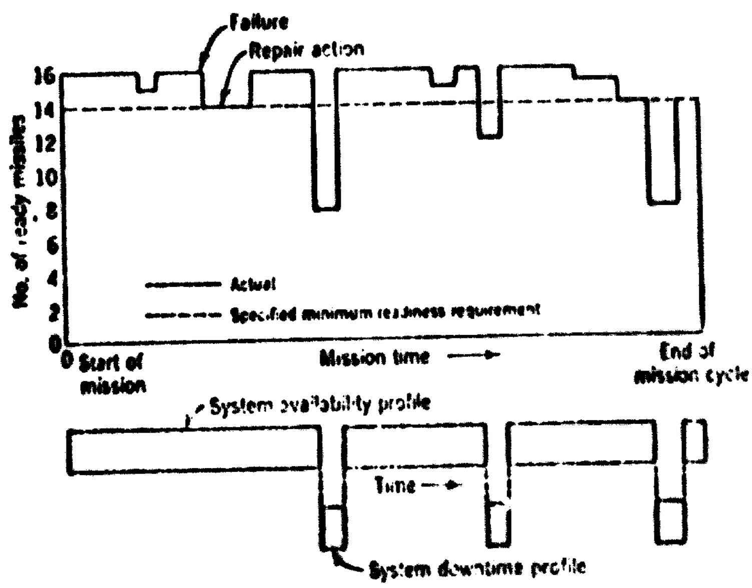

Figure 1 Mission profile for pypothetical missile squadron x)

Figure 2 predicts how operational availability requirements can be converted to R & M requirements within the constraint of the mission. As shown, several alternative combinations of R & M requirements can be attained for any availability level.

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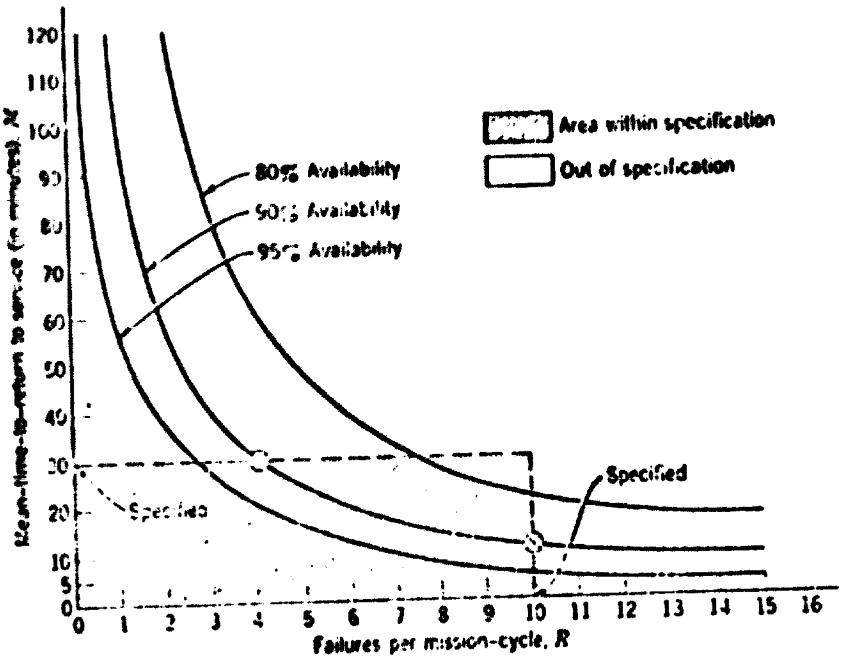


Figure 2 Reliability (R) versus Maintainability (M) trade-offs

The need for cost minimizing among R & M alternatives that meet mission requirements means that trade-off studies between reliability and maintainability are necessary before deriving final M requirements. The next example shows how a computor can be used for simulation in provisioning analysis. The example deals with setting up a spare list for a guidance computer in a polaris submarine.

A polaris submarine goes on patrol for a given period of time with no possibility of having spare parts etc. During the patrol all missiles must be ready for action at all times. To illustrate the approach to this problem, the availability concept in connection with the guidance capsule of the polaris missile will be chosen.

Since component repair is not considered practical on a submarine maintenance action very often is a question of removal and replacement of plugg-in units; spares are therefore carried in this form.

There are three objectives in this problem.

1. Determine the effect of alternative provisioning and check out procedures on the operational availability of a major sub-system on a patrol of any length.

2. Determine the check out interval which will maximize operational availability over a fixed period patrol.

3. Establish a preferred spares list which will maximize operational availability over a fixed period patrol within constraints inpost by cost and engineering feasibility.

The operational availability can be defined as

$$A = \frac{\text{Number of missile-hours "up"}}{\text{Total number of missile-hours}}$$

Figure 3 gives availability profile for the best and worst (from this standpoint of operational availability) of several cruises with missiles equipped with the exemplory guidance system using a specific spare part list and an optimal check out interval. Number of Missiles "up" are plotted against cruise hours elapsed.

The main divergence between the two cruises took place in the latter period of the cruise which ran out of a key spare which put out several missiles. The result was that the cruise ended with only eight missiles "up". For the "superior cruise" all missiles were "up" at the end.

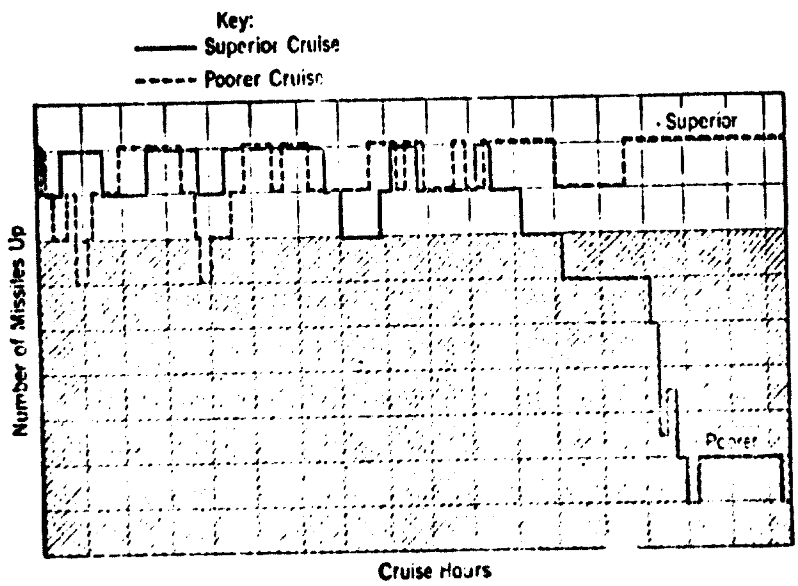


Figure 3 Hypothetical operational availability profiles

The Swedish army has recently made a decision to renew their trucks. The procurement of these have followed entirely new lines. The truck supplier chosen can show the lowest total cost during the life span of the truck. When this criteria is used the maintenance costs are of high importance.

The basic idea is that the producer shall minimize the maintenance cost by building in maintainability and maintenance quality in the design. The delivery check contains various running tests and storage tests. These tests are performed in order to represent normal conditions. An incentive plan is included in the agreement. If, at the test, the calculated milage cost will be lower than in the invoice, the manufacturer will receive additional payment. That is proportional to the expected savings. If the opposite happens the sum invoiced will be reduced. This insures that the producer even after the negotiations is interested in low maintenance cost of the trucks. By checking the maintenance quality at the delivery of the trucks, it is possible to reach an agreement that insures a minimum milage cost. This technique will also be possible in large scale procurement of production equipment. It is an advantage if such negotiations could be carried out on the country level.

3. M IN THEORY

3.1 M vs availability and reliability

Attaining a desired level of system availability requires a complex process involving many resources of which system reliability and maintainability requirements are generalized characteristics describing system performance during a time period. The form used to describe system availability is that of an expected value function which assumes a steady state condition:

$$A_s = \frac{MTBF_s}{MTBF_s + MRT_s + MTWS_s}$$

Where A_s = Availability of the system

$MTBF_s$ = Mean-time-between failures of the system, reflecting reliability

MRT_s = Mean-time-to-repair, reflecting maintainability

$MTWS_s$ = Mean-time-waiting for a spare, reflecting supply

This equation can also be generalized: $A_s = F(R_s, M_s, S_s)$

Where

A_s = Availability

R_s = Reliability

M_s = Maintainability

S_s = Supply efficiency

This availability function may best be demonstrated with a geometric model. In order to demonstrate certain principles the equation of availability is presented in the form of response surface in which reliability and maintainability are variables (Figure 4).

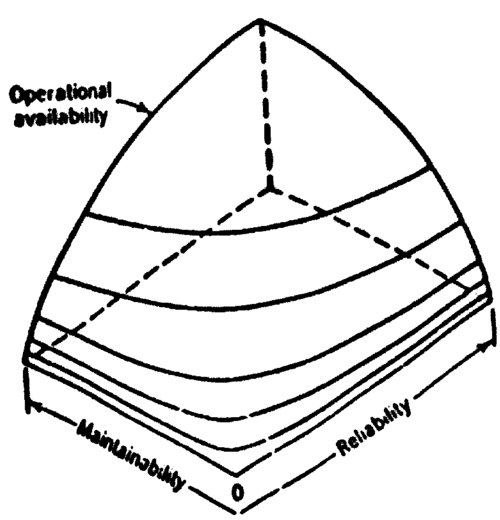
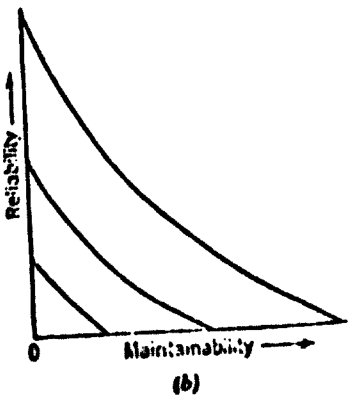


Figure 4 Hypothetical availability surface

Figure 5 illustrates the contures of figure 4 in which reliability and maintainability substitute at a diminishing rate over a limited range, but have zero substitution beyond this range.



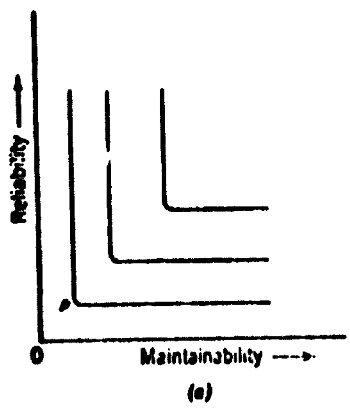
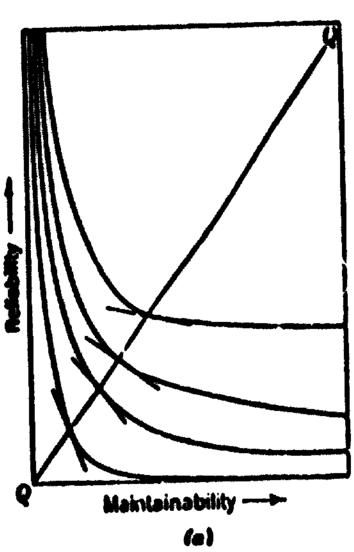


Figure 5 Isoavailability contours

Figure 6 Isoavailability contours

In figure 7 the slope of the line QQ represents a fixed ration between reliability and maintainability.



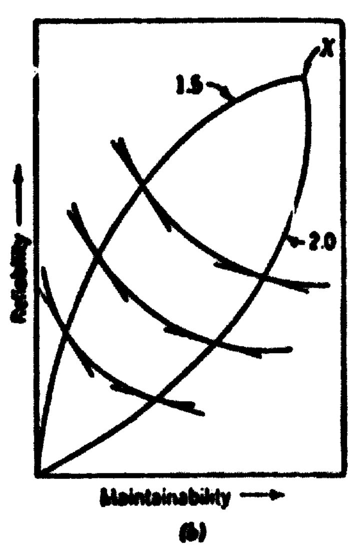


Figure 7 Isoavailability functions showing a fixed ratio

Figure 8 Isoavailability functions and locus of points having same scope (isoclines)

In figure 9 we represent the extreem bounds on an isoavailability function map by means of two isoclines.

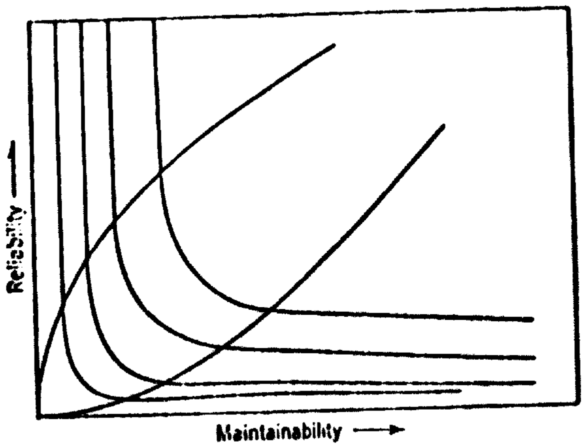


Figure 9 Boundary lines on a contour map

The upper isocline connects all points having an infinite slope, whereas the lower isocline connects all points having zero slope.

3.2 Distribution of down-times

The distributions most commonly used are

- negative exponential
- lognormal

The general shape of these distributions is shown in figure 10. Another distribution that could be given increased attention as a substitute for the lognormal is the Gamma distribution, because it is easy to handle mathematically.

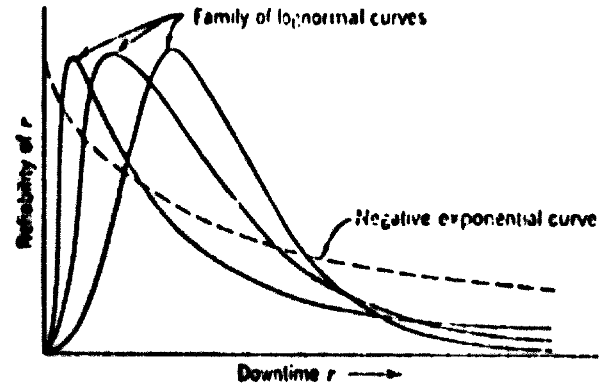
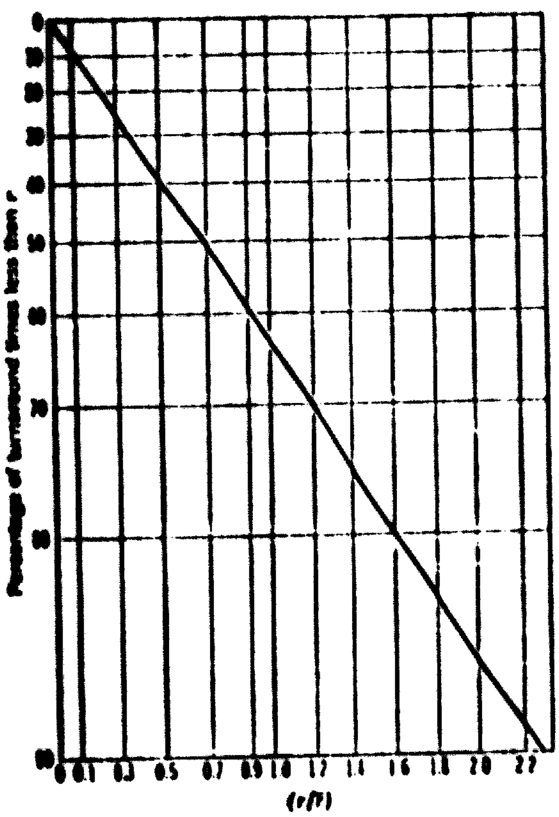


Figure 10 Possible distribution of down-time

The exponential distribution can be found in simple systems and equipments.

The negative exponential distribution plots as a straight line on semilog paper, see figure 11.

Figure 11 Ratio of down-time (r) to mean turnaround time ($\bar{r}$) - negative exponential distribution



Its distribution function is:

$F(r) = e - r/F$

where F is the mean turnaround time.

The lognormal distribution describes the down-time for a wide variety of reasonably complex equipments.

On logaritmic probability paper similar to that shown in figure 12, the number of hours is plotted on the logaritmic vertical scale along with the percentage of all down-time less than or equal to this value on the probaility scale.

Figure 12 Mean down-time (F) - log-normal distribution

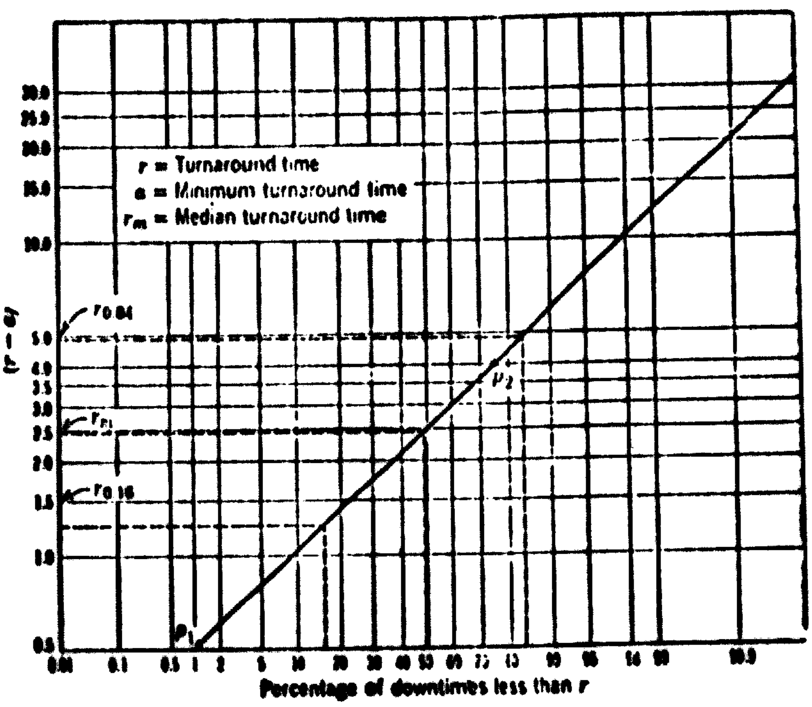
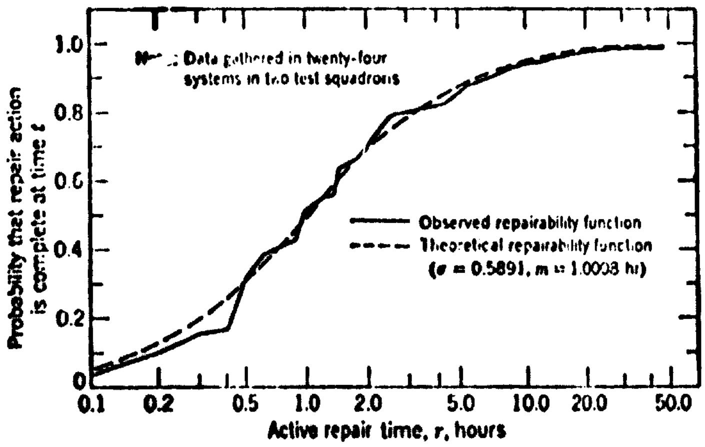


Figure 13 shows a typical fit on a down-time data by a log-normal distribution.

Figure 13 Observed and theoretical repairability functions



It is possible to study maintainability in a quantitative way by studying the down-time of an equipment. Down-time provides a means to formulate a function of system characteristics, operational parameters and operational effects.

The following elements can be combined to yield system operational availability as shown in figure 14.

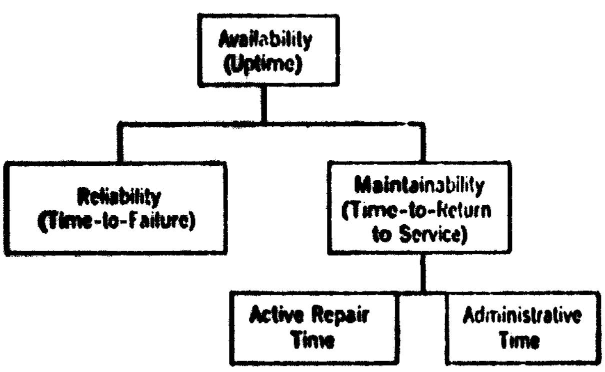


Figure 14 Relation of maintainability elements to availability

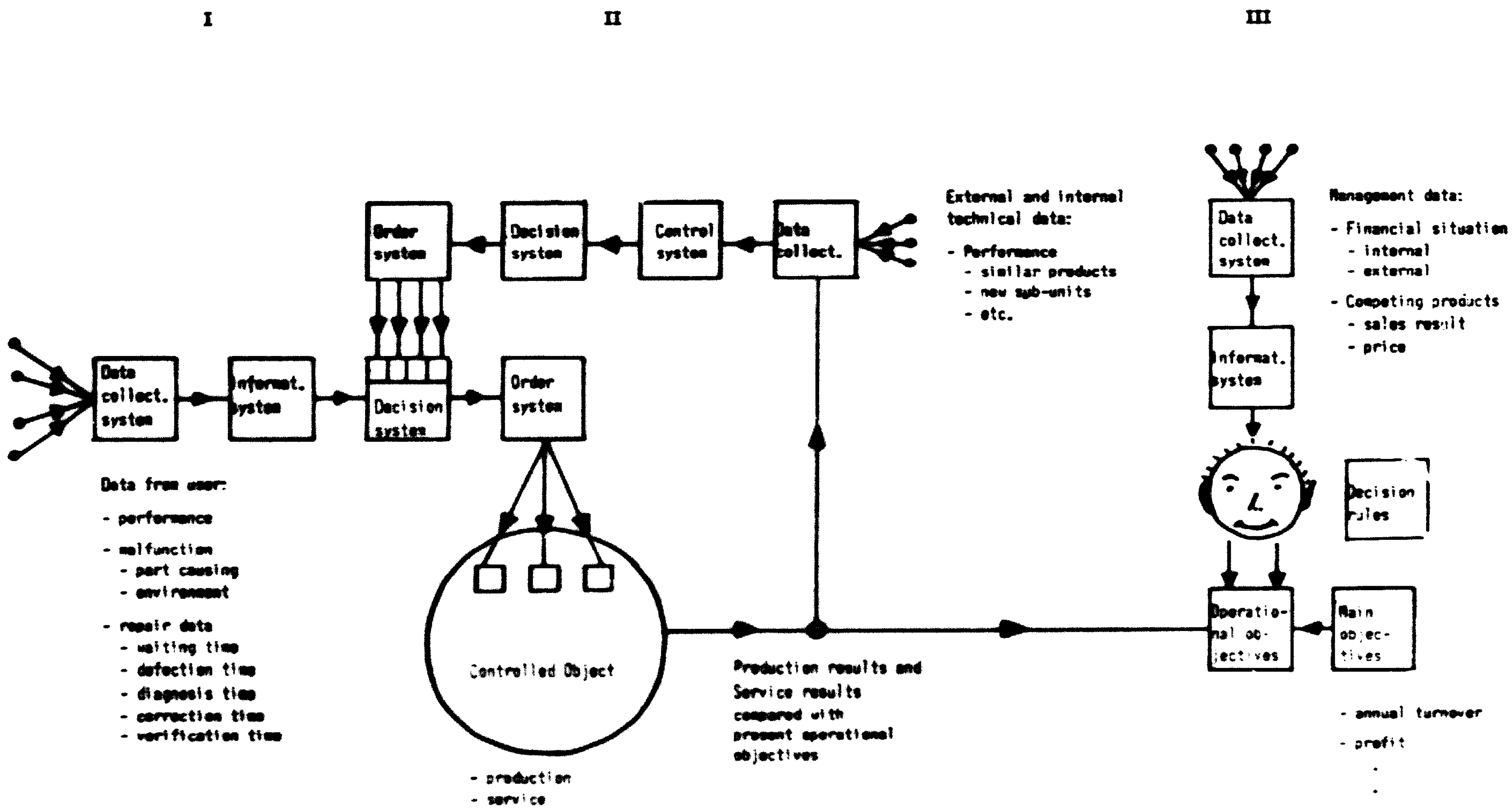
3.3 M and the flow of information, a Management Information System Approach

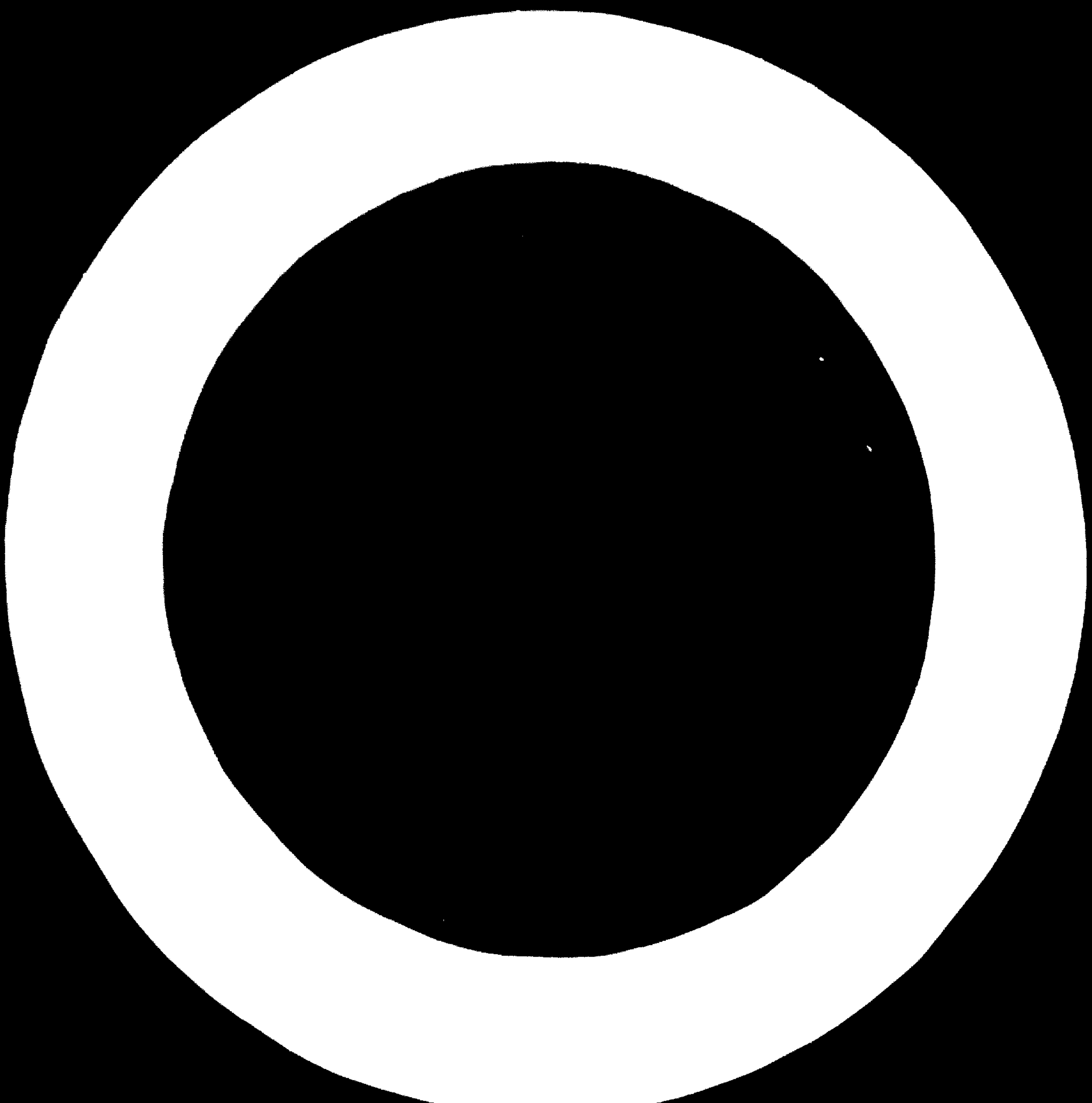
The following chapter serves to place Maintainability, Reliability and Availability as a part of the information of a Management Information System, consider the company that produces an item of considerable complexity. It is highly important that the design department of the company has a thorough knowledge of the performance of the item after it has been sold. The sale´s result is to a very high extent dependent on the users´ experience of the item. This makes the feedback of information from user to producer of vital importance as this may initiate actions of modifications that may rise the sale´s result and customer´s satisfaction.

Figure 15 shows one way to illustrate a Management Information System. The information flow consists of Maintainability, Reliability, Availability and Information that is associated to these.

The system consists of three information chains:

Figure 15


I
II
III
Data collect. system
Informat. system
Decision system
Order system
Decision system
Control system
Data collect.
Order system
Controlled Object
Data from user:
- performance
- malfunction
- part causing
- environment
- repair data
- waiting time
- defection time
- diagnosis time
- correction time
- verification time
- production
- service
Production results and Service results compared with present operational objectives
External and internal technical data:
- Performance
- similar products
- new sub-units
- etc.
Data collect. system
Informat. system
Decision rules
Operational objectives
Main objectives
Management data:
- Financial situation
- internal
- external
- Competing products
- sales result
- price
- annual turnover
- profit



No. I - Product data from user.
Collected data is checked against pre-set parameters. Deviation might initiate re-construction or re-organisation activities.

No. II - Production and sales feed-back chain.
Production and sales result together with external information is collected and fed back into chain No. I, in order to control the parameters of system I.

No. III - Top management information chain.
Data for top management is collected in order to aid the manager to control the operational objectives.

Information chain I

Data collection

The relevant information about the performance of the sold item is collected. The buyer can supply information about the hours in production, down-times and quantitative and qualitative production results. When a mal function occurs, the part number of the faulty part is given and the environmental factors at the time is of interest. This might be: speed, type of production, oil used, and so on. When the fault is corrected by the buyer or the user, the times in connection to the repair is given. If serviced by the maker, the repair man's name is collected.

Information system

The collected data is computed with the aid of the statistical formulas and/or operations research in o useful information. This might be:

- Availability for different items presented in the form of total up-time devided by total time.

- Reliability of various items. Or of parts in different environments presented as MTBF-values.

- Maintainability of different parts presented as average MTTR-times. Interesting information can also be waiting times in different service areas or repair times, diagnosis times and correction times sorted by type of part repaired or repair man.

Decision system

A "management by exception" thinking must be applied, in order not to "over-inform" the management. In the presented "Management Information System", the decision system contains pre-set parameters which control what information shall be presented. This means for example that data outside the one or two sigma-points of the normal distribution is given together with the mean values. When a component or a part in a unit for one user exceeds the pre-set accepted upper limit, this might initiate a contact with the user in order to find the cause.

Order system

The non-tolerable values are distributed to the appropriate department by the ordering system in order to insure that appropriate actions will be initiated.

The sale's department receives the availability values for different items to be used as a sale promotion material.

Top management might be interested in availability figured to be informed about performance of the item.

Design departments receive the maintainability, reliability and availability data of the item and it parts in different environments in order to find out the modifications that are necessary to insure a fruitful and economical research and development to rise availability or bring down repair times.

The information about waiting-times, detection-times and correction-times sorted by service-men is of vital interest for the service department. Untolerable deviations might initiate for example: training of a specific repair-man on a certain sub-unit in order to bring down repair-times on this unit. High waiting-times might be a result of a too large service area or a too small repair-crew in a specific area.

Information chain No. II

The principal task for this chain is to set correct parameters in the decision system of chain No. I.

The data is handled in a similar way as the previous system.

All necessary data is first collected. This might be production and service data. Modifications of sub-units may make it necessary to predict new reliability and maintainability parameters. Changes of waiting-time distribution may be expected from an re-organization of the service areas etc. External technical data from the development of new material and products is compiled.

Information chain No. III - Management Information

The board of directors of most companies decide each year upon the main objectives, as minimum annual turnover, profit etc. In order to simplify for management these objectives are broken down to operational objectives, such as sales per month, service costs, performance of product etc. This chain collects and compiles management data in order to make it possible for management to update the operational objectives when necessary. The manager might be assisted by some decision rules when updating. The data collected from production and service is compared with the operational objectives and deviation might initiate top management to make a proper decisions in order to restore the situation.

This was a very brief description of the role that maintainability, reliability and availability as a system characteristic can have in a Management Information System (MIS), designed for a producer of a complex product. Of more general interest is a MIS to collect M information from any industrial process. This can be made part of any manual or computerized Maintenance Management Information System.

4. ELEMENTS OF M

4.1 Maintainability vs design

Design can be looked upon as a pre-construction or pre-procurement phase. Consequently, most characteristics mentioned under "Purchase vs maintenance" will be applicable to design as well. We will, however, stress some of the items a bit more and add a few new ones.

To build in a high degree of M already during the design phase the following measures shall be taken:

- The design department shall regularly collect information from the M technician at the maintenance department (see "Maintainability vs maintenance").
- The design department shall develop an internal design standard which also will be applicable to procurement situations.
- Together with maintenance and purchasing departments a standard stock material and component list shall be developed. A designer is not allowed to specify units which are not part of the list.
- Every new design shall be checked against a M Checklist.

The following list is a condensed version of the list in chapter 4.2, and serves as an example aimed to give some inspiration.

1. Has sequential assembly been avoided which results in involved disassembly and assembly when performing repairs and adjustments ?

2. Is the right kind of material chosen?

3. Are vital parts redundant?

4. Are the highest failure rate components readily accessable for replacement?

5. Are cables and pipes easily disconnectable?

6. Are plugs - in units - keyed to prevent wrong insertion?

7. Are test and check points adequate?

8. Can the machine be manually or semimanually controlled when the automatic control system is out of order?

9. Are special tools necessary and if so supplied?

10. Does the machine consist of standard elements?

11.. Standardization?

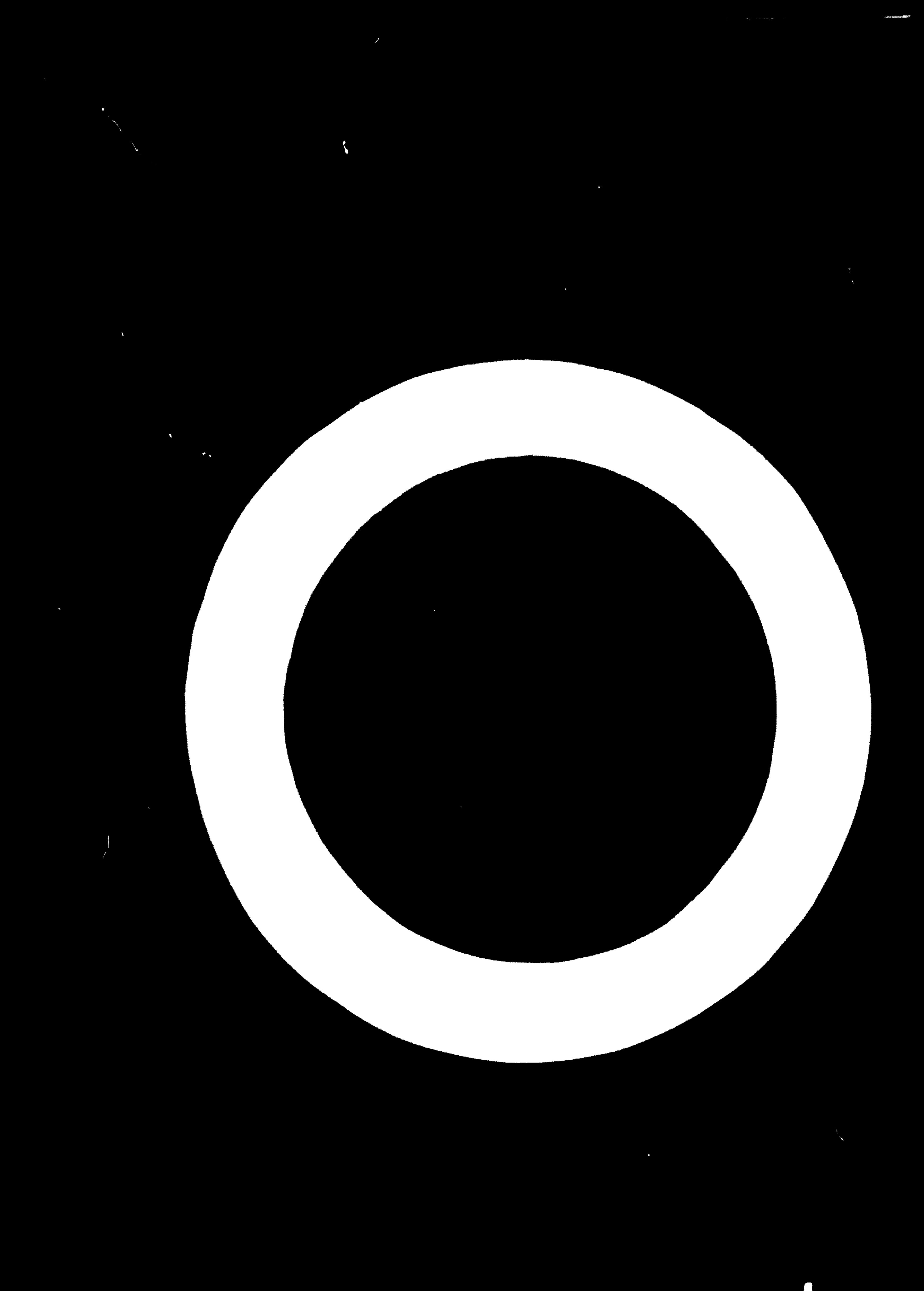
12. Is periodic alinment and/or adjustment necessary? How often?

13. Does the unit require a special handling?

14. Is inspection possible without disturbing the machine performance?

4.2 Maintainability vs procurement

The procurement of equipment for industry is essential. The decisions made may affect the profit of the company for many years. A better decision could be made, if according to our experience the following three things are remembered:



1. A procurement decision must be made by a group of people from production, maintenance and procurement departments.

   An equipment will very likely be used for 10-15 years. During these years it will need maintenance and maintenance cost money.

   The maintenance cost amounts to 3-7 % of the purchase price so the accumulated maintenance cost during the life span of the equipment may exceed the initial investment.

2. The agreement between the buyer and the supplier shall be as detailed as possible and include a guarantee clause of some kind.

3. The full price shall not be paid until all the specifications within the agreement are satisfactorily fulfilled.

To aid the procurement group in making a "right economic" decision, a maintainability check-list will be discussed.

The major factors that affect M are:

- Design characteristics
- Operational characteristics
- Maintenance personnel qualifications
- Training in trouble shooting and repair experience
- Maintenance organisation
- Repair shop facilities
- Spare parts logistics

- Test equipment
- Tools
- Handbooks

The effectiveness with which each factor is handled and the balance achieved among them will determine the maintainability level. The obtained level could be evaluated in terms of one or more of the following criterias:

1. Maximum operability of maintained equipment
2. Minimum time for maintenance
3. Minimum cost (all factors)
4. Minimum risk of injury to personnel
5. Minimum on the job training
6. Minimum equipment failure or damage
7. Maximum collection of failure and repair data

When evaluating the degree of maintainability of an equipment, the following is of interest:

Design characteristic to improve maintainability

The bolts and nuts that are subject to corrosion could sometimes be made of stainless steel to make maintenance on the whole possible.

Consider a cooling pump the functioning of which is vital to the machine. Failure of this pump might cause a very costly break-down. Two pumps working in parallel improve the R and M considerably.

Check that break-linings, belts, coupling elements etc are located in such a way that a disassembly of a whole component or a machine is unnecessary when replacing such items.

The nuts and bolts shall be either of metric or inch size, not both. The gear boxes shall be built with gears of standard modules. A non-standard gear may cause unnecessary long break-downs because a spare must be shipped and cannot be made in a maintenance department or elsewhere nearby. It sometimes seems as if the maker of the machine tries to enforce the user expensive non-standard parts, where standard parts could be used. The number of electric motors of different sizes should be kept to a minimum. The cost of the equipment may be slightly reduced by choosing minimum effect motors but that causes the user to have a troublesome number of electric motors in stock.

Information and handbooks

1. Are detail drawings supplied with the equipment?

   Manufacturing of spares are sometimes necessary. Detail drawing makes this possible without dismounting and measuring.

2. Is an economic optimal mix of spare parts suggested?

3. Is the equipment supplied with a list and/or a drawing of oil and grease points?

4. Are preventive maintenance activity and intervals suggested?

5. Is the instruction-book and other documentation written in an understandable language?

6. Is reliability data supplied?

Testing and test equipment

1. Is test and diagnostic equipment suggested and/or supplied?

2. Are test and check points easily accessable?

Miscelaneous

1. Which spares will be supplied from the manufacturer?

2. How many years will the manufacturer supply spares?

3. Are simulation of maintenance activities necessary to be able to foresee crew size etc?

   Maintenance simulation is very difficult to carry out, unless there is access to a Standard Data for maintenance work.

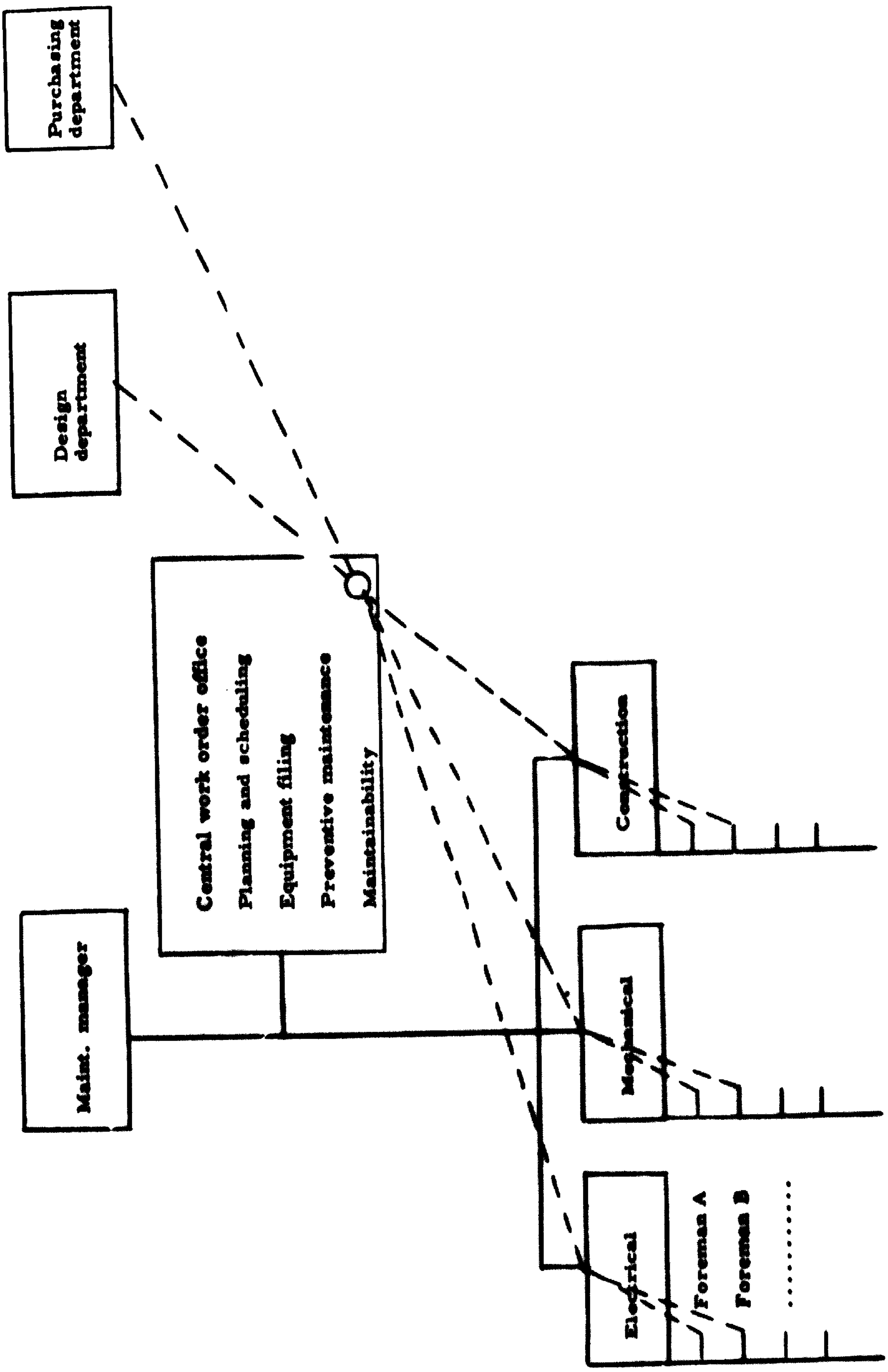
4.3 Maintainability vs Maintenance

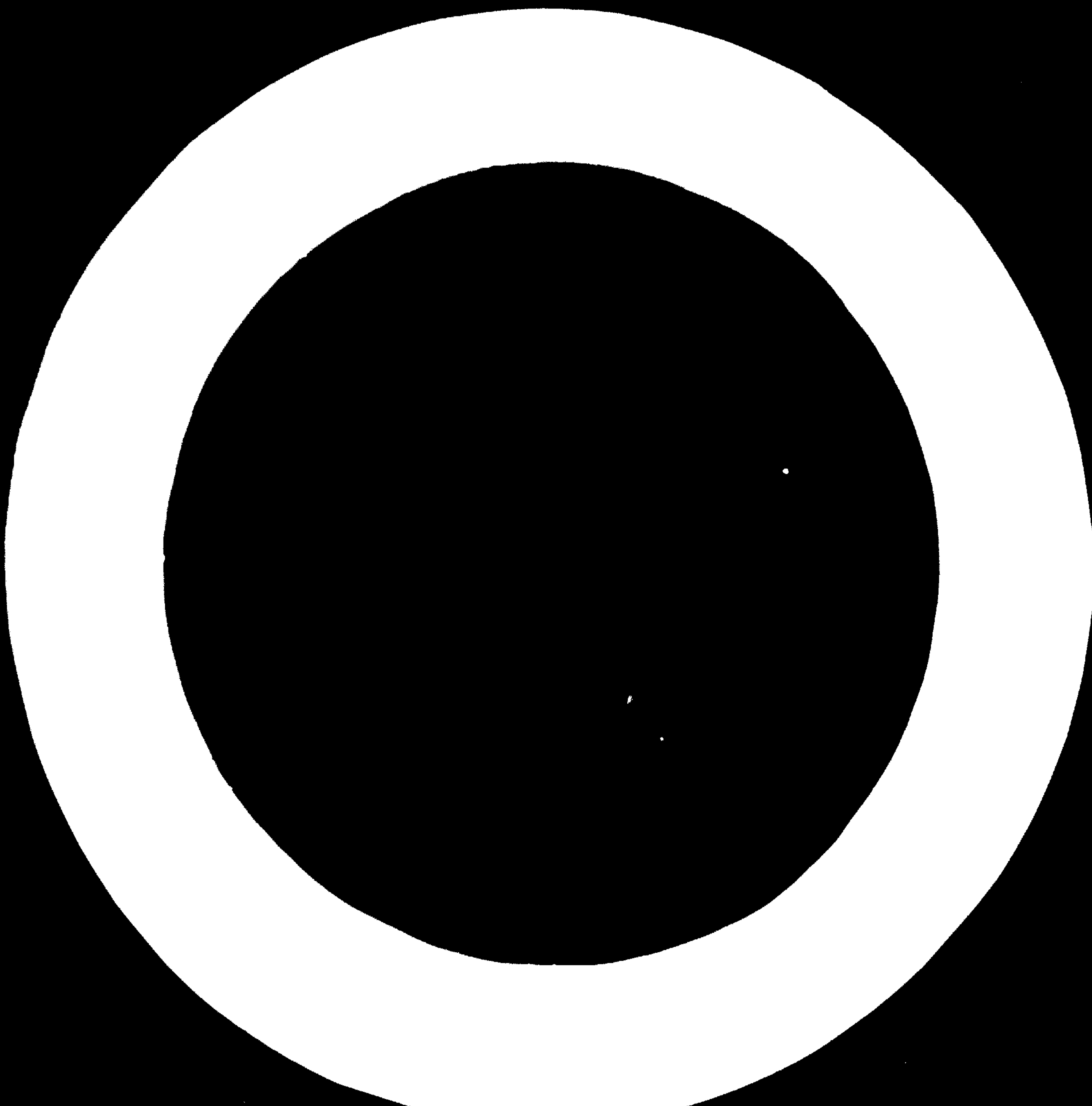
Maintainability versus design and procurement could be characterized as the "before-the-fact-approach to M". At this stage the equipment is not in production. We will now also penetrate M on equipment already installed - the "after-the-fact-approach to M". Basically, M could be looked upon as three different functions which back up each other:

1. Follow-up and enlargement of M efforts made by procurement, own design department and machine manufacturers' design departments.

Figure 16

M in the maintenance organization





2. Reporting of bad M cases on the production equipment now running. This reporting has two purposes:

   - Equipment with bad M characteristics shall not be purchased again.
   - Feasible changes in equipment design shall be made to rise M level.

3. A "doing" function which designs out and changes weak M cases reported by function 1 and 2. This "doing" function can be the regular maintenance work forces.

The three functions above shall be handled by different parts of the maintenance organization to avoid the growth of a too expansive and comprehensive M organization. There must, however, be one person responsible for the coordination of M efforts within the maintenance organization.

This "M technician" could be placed in the organization structure in very much the same way as the Preventive Maintenance technician. Figure 16 is a simplified organization chart where the dotted lines show the M technicians main channels of contact with other functions. We like to stress that this is not the same as subordination or responsibility.

We will now a little more in detail explain the M technicians' duties and responsibilities. At the same time this gives an understanding of how M is treated within maintenance.

Duties and responsibilities for M technician

General

- The M technician is coordinator for all M activities within the maintenance department.

- Collect M information from production and cost statistics.

- Collect M information from the maintenance crafts preferably by means of a formal information system.

- Evaluate received information and suggest actions to be taken. He is supposed to act according to one or more of the following patterns:

  1. After a feasibility study decide if the equipment shall be modified.

  2. By means of the ordinary maintenance work order system request modification jobs on the equipment to rise M level. Eventual design work shall be done by the M technician himself or if too extensive he shall request assistance from the design department.

  3. From his experience recommend new or revised M rules for the purchasing and design functions.

- Co-operate with the design and purchasing departments in M cases. Scheduled meetings with the people handling M are highly recommended.

Repair and maintenance instructions

- Order missing maintenance manuals, drawings etc.
- Expand and revise manuals when equipment is changed.
- Make a standard manual for repair and maintenance instructions. This manual will be used as a model when developing new manuals and when purchasing new equipment.

Methods

Together with the standard data development section the M technician shall follow up.

Tools

The M technician shall take part and propose development of:

- personnel-tools and
- tools assigned to certain equipment.

He shall also follow up the general development on the tool market.

Training

The M technician shall take part in the training activities for the maintenance crew. Maintenance work mainly consists of trouble shooting and repair. Our experience is that the biggest time saving possibilities can be found within trouble shooting.

Standards for maintenance works

- Use an eventual standard data system to bring maintenance time to a minimum on equipment with high down-time costs. A standard data system is the most effective tool for methods' development and comparison of maintenance methods.

5. PRODUCTION SYSTEMS AND INFLUENCE ON M

Like the use of most other functions in the company management and use of the M function is the use of scarce resources. We must consequently use the M capacity as effective as possible. The following rules could be of some guidance:

1. Production down-time costs

A production system is designed in one of these basic concepts:

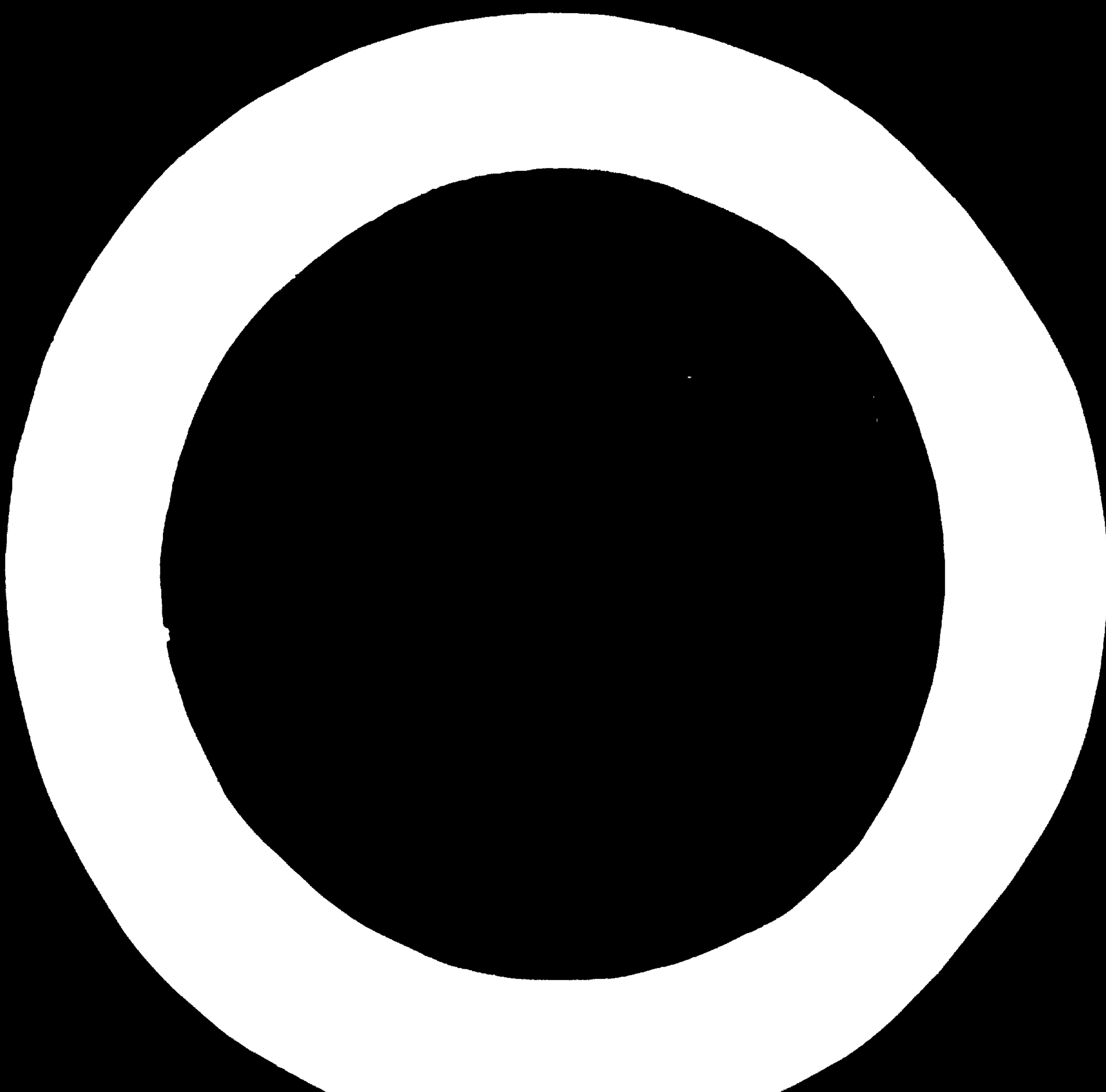
- Batch processing
- Line processing
- Continuous processing

The concept used influences the stress laid on M efforts. Continuous processing has the highest break-down costs due to production loss and M efforts in this type of industry will pay off very rapidly. This is a very general rule but for the individual company a more specific guidance rule can be given. We can assign the equipment into groups according to their importance to the production operations. The lowest group is the most important where M efforts should be emphasized from the down-time costs' point of view. An example of such an equipment grouping system is found in figure 17.

MAINTAINABILITY (M)

EQUIPMENT GROUPING SYSTEM TO ASSIGN M EFFORTS

Code Name	Description of the Equipment
1. Major Utilities	Major utilities equipment influencing more than one production unit. Includes electrical distribution lines. (Utilities affecting only one production unit carries the code of that unit).
2. Key Production Equipment	No stand-by equipment available. Includes necessary service units such as cranes and conveyors.
3. Miltiple Production Equipment	Units for which stand-by equipment is available. Includes necessary service units, such as cranes and conveyors.
4. Handling Systems	This category includes the necessary service lines-conveyors, chutes, etc.
5. Production Equipment	Includes all necessary service facilities, and overhead cranes not tied cirectly to process.
6. Service Facilities	Includes all necessary service facilities.
7. Production Equipment Spares	Includes all necessary service facilities.
8. By-products	Includes all necessary service facilities.
9. Buildings, roads and offices	Includes those not directly influencing production.
The classification is an example.	Individual design is desired.



2. Maintenance costs

Maintenance costs could be high for a certain machine due to the following reasons:

1. High wear
2. Wrong handling
3. Bad design from the M viewpoint.

In anyone of these cases it will usually pay off very rapidly to look at costs from the M viewpoint. Can we out-design high wear or bad M? Change maintenance methods? Use other tools? Train the operator to use the machine correct?

To make a simple rule-of-thumb to be used in choosing between cost reduction areas, e.g. in production or maintenance is in theory very simple: Reduce the highest cost first. In practice it is very difficult to make the right decision. The M people are therefore advised to use experience, common sense and simple calculations as guidance.

6. CASE

For many systems and sub-systems a primary parameter of interest in evaluating the systems' effectiveness should be the average operating time during a mission of relatively brief duration or a fixed period requiring continuous operational capability. This case is an example of an availability concept which utilizes reliability and maintainability statistics to obtain high availability during a continuous mission with repair.

Maintainability can be defined as the capability of an equipment to be returned to an operational status in a specified period of time. This case describes an information system that places the subject area of maintainability, reliability and availability in its context as a system characteristic. The philosophy behind the information system in this case follows the same basic lines as the Management Information System in chapter 3. 3.

The case will show the information system built up specially for an automatic blood serum chemical processor built by the AGA Medical Division in Sweden, named the AUTO CHEMIST.

The AGA AUTO CHEMIST is presented in the broschure enclosed. Although it is described in the broschure, it is necessary to give a very brief presentation together with the maintenance aspects of the unit.

These are the sub-units of the AUTO CHEMIST:

- A central chemical processor, which is loaded with the samples and performs the chemical part of the analysis,
- Operation is govern by the ELECTRONIC CONTROL UNIT,
- Readings are transmitted to a computer,
- An electric type-writer delivers the result in printed form,
- Power unit,
- Regulator unit,
- Master control unit.

The central chemical processor is the central unit for chemical processing. Here the patient blood serum samples are split up into subsamples, one for each channel where one determination is made. There arc 24 basic analytical channels in four analytical groups. Mechanical conveyor systems move the samples from station to station. Pneumatically regulated pipettes add reagens. The samples are heated in an incubation box and cooled in a cooling bath. Photometers measure the reaction solutions.

The electronic control unit governs the mechanical functions and timing of the system.

The master control unit contains a start panel with controls for manual and automatic starting.

Readings are transmitted to a PDP 12 C-computer. The computer produces reports in a convenient form for sending to the physician. The reagent supply system consists of diafram pumps and pressure regulators.

The amplifying unit contains one amplifier for each photometer measuring head in each channel.

A flame photometer has been adapted for the measurement of three elements:

- Sodium,
- Potasium and
- Calcium.

MINI CUBE is required when incubation temperature is higher than 50° C. The MINI CUBE contains an oven made of glass and teflon, photometers and washing arrangements.

The power unit delivers current to motors, photometers, lamps, amplifiers and control units.

The AUTO CHEMIST contains many high precision sub-units that operate under very severe conditions. An example of this are the many pipettes which add a few millions of a liter of, for example, sulphuric acid with high accuracy into the samples.

The AUTO CHEMIST has a high capacity. It can perform up to 50 000 determinations a day.

Several AUTO CHEMISTS are spread around the world. Some of these run up to 20 hours per day and process up to 2 000 blood serum samples per day. The vital information supplied by the AUTO CHEMIST is given to the physicians in order for them to make an accurate diagnosis. Because of this the maintainability, reliability and availability must be brought to the highest attainable level. In order to obtain this degree of availability and security, it is necessary that all important information is fed back to the AUTO CHEMIST manufacturer.

To properly evaluate trade-off decisions between availability, maintainability and reliability of a system of present and future design requires combining system analysis determinations o: the probability of mission success, with reliability, maintainability and availability analysis to obtain a measure of system effectiveness of probability of mission success. The information needed falls into three different groups:

- Performance follow-up
- Service follow-up
- Failure follow-up.

6.1 <u>Performance follow-up (PFU)</u>

It is of vital interest for the AGA Management to follow up the performance of the different AUTO CHEMISTS. Information is supplied about:

- System availability
- Amount of unacceptable analysis per day, - "up time" and "down-time"
- Maintenance cost
- Number o.' break-downs per month and their distribution on different sub-systems.

A total performance average covering all AUTO CHEMISTS of the different figures are given as to serve as a standard against which each unit is compared. Any deviations may easily be seen and action can be taken.

6.2 <u>Service follow-up (SFU)</u>

Until recently, the design of systems proceeded with minor consideration of the capability of technicians in the field to maintain them effectively. In the scramble to meet operational requirements, the requirements for easy maintenance often got lost completely, or at best, were regulated to a low priority status. The consequences of this narrow emphasis have been unbelievably costly to the users of these systems.

Not only has consideration of the human element in maintenance been late, but also the development of useful quantitative descriptions of the technicians' performance capabilities has lacked far behind our ability to establish quantitative specification in other areas. The SFU gives information about human factors in maintenance from the viewpoint that the maintenance task cycle, as derived from systems' "down-time" requirements, is the starting point for work on maintainability problems.

The SFU describes the technicians' performance and aimes at answering the following questions:

- What do we know about the technicians' capability for performing maintenance?
- Where are the generally hard spots?
- Where do most technicians tend to make the most errors?
- What are the ranges in proficiency in a population of technicians in performing maintenance?
- Given particular equipment or system and a particular population of technicians, can we predict time or error performance sources?

Although the maintenance task cycle is one element of the maintainability problem, we know that maintenance is not performed in isolation. The equipment that requires maintenance is diverced in structure, configuration and function; the environment often seriously attenuates human performance; there are limits to the knowledge and skill of technicians; and management and support factors usually are less than ideal. As illustrated in figure 18 a complex of interrelated factors determines the quality of the maintenance, that is performance in the field. Maintenance is done always in contexts in which these factors exist. Each can effect the quality of the maintenance that is performed; indeed, an extreme of any one factor might drastically alter the whole performance picture.

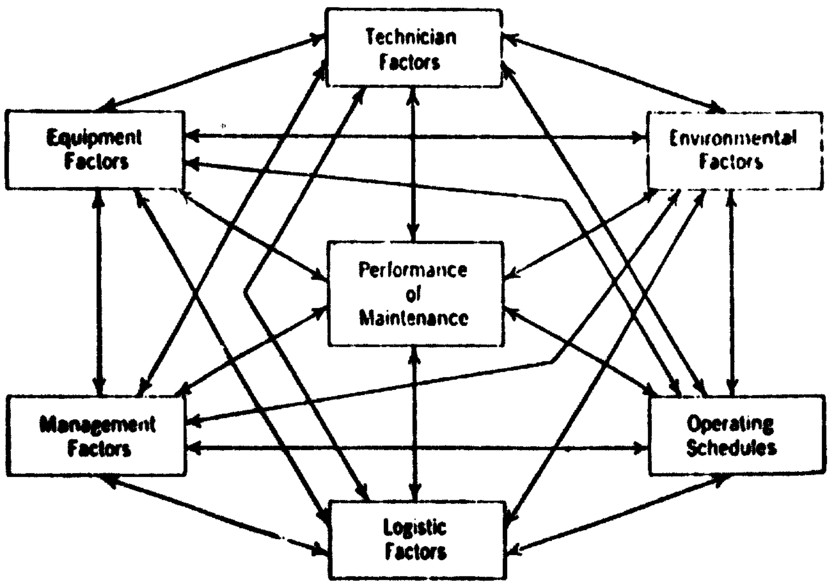


Figure 18

Factors which affect the performance of maintenance in the field.

6.3 Failure follow-up (FFU)

The failure-follow-up-system shall be an aid to the engineering, production and quality control functions in their efforts to reach the optimum of reliability and economy in the operation of the AUTO CHEMIST:

The FFU-system shall thus assist the ENGINEERING FUNCTION in:

- Designing and dimensioning preventive maintenance,
- Indicating methods to find and remedy failures,
- Choosing the best component for every task,
- Checking the reliability of the preventive maintenance,

- Finding the correlation between different failure types and environmental parameters,
- Finding the cause for deviations in total system availability of different AUTO CHEMISTS,

and the SERVICE FUNCTION in:

- Planning and performing preventive maintenance (maintenance and overhaul),
- Finding and remedy failures (trouble shooting),
- Estimating and satisfying material requirements.

6.4 Information System

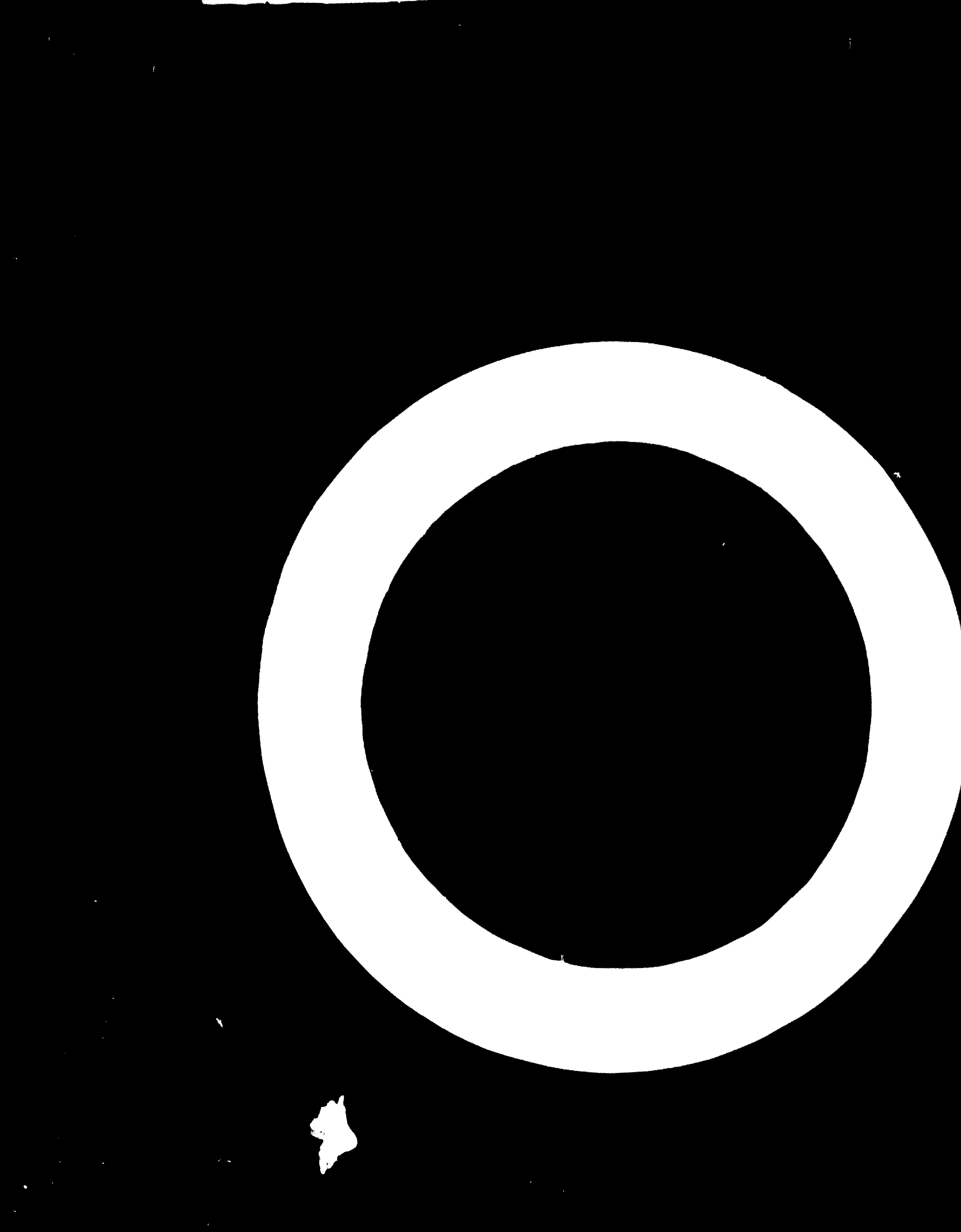
Input

In order to be able to present the output information previously described, it is necessary for AGA to receive the following information from every AUTO CHEMIST:

Log

The log form collects information at the end of each shift for every AUTO CHEMIST. The following information is collected:

- User's name
- AUTO CHEMIST number
- Shift start date
- Total elapsed hours
- Expected number of analysis



- Accepted number of analysis
- Non-planned down-time (hours)

Action report

All maintenance actions performed on every AUTO CHEMIST will be reported on an action form. The following information is nessecary:

- User's name
- AUTO CHEMIST number
- Date
- Sub-system
- Analysis
- Number of components
- Failure type
- Action caused by preventive maintenance: Yes - No
- Component exchanged: Yes - No
- New type of component installed: Yes - No
- Defective component thrown away or returned: Yes - No
- Number of new type of component
- Repaired by own personnel: Yes - No (person number if repaired by AGA)
- Waiting time for service man
- Repair time

This is the main input supplied to the information system. About 1 000 forms arrive to AGA every week. These are converted into punch cards which at certain intervals are read by the computer. By means of different statistical equations the information is compiled and calculated and printed out.

Output lists

Before describing the output list it must be emphasized that all lists shown are dummies and all figures therein are highly fictitious. The basic philosophy behind all lists is that it must be possible to evaluate every figure presented without comparing with figures from other or previous lists. Hence every value for the last month will be presented together with the average of the same value for the last twelve months and the average of all Auto-Chemists during the last month and twelve months. In this way, any deviation will be easily found.

List number 1

The performance of all Auto-Chemists can easily be followed up by means of list numbers 1 and 2. List number 1 compares the performance parameters of all Auto-Chemists in the system. Availability is defined in a non-conventional way. It is not the ratio between "up-time" and total time but the ratio between accepted numbers and expected numbers of analysis per month (.972). The same ratio for the last twelve months is calculated for comparison (.953). The availability for an Auto-Chemist cannot only be compared within itself but with the average availability of all Auto-Chemists during this or the last twelve months.

The availability figure alone does not give enough information. In case of break-down the work done by the Auto-Chemist must be performed manually. The manual analyzing capacity at a laboratory is a fraction of the Auto-Chemists. This makes it more serious when a large number of samples are lost one day than if a small number is lost every day. Because of this, the maximum number of lost analysis of any day during the months is printed out (72). A twelve months' average is also printed (30).

The list also gives the "up-time" and "down-time" -values for all units and a total average for one and twelve months. The standard availability figure can be calculated from these, if needed. It is a necessity if the unit were on a leasing basis.

The number of maintenance actions on every unit of the last months and an average over twelve months is printed out. In order to find the cause for any deviation of previous figures, the number of actions caused by the different sub-units are given. This shows which sub-unit that causes the trouble and will initiate the printing out of a more detailed information. This will be described in list numbers 4 and 5.

List number 2 (not shown)

This list gives the same values as list number 1. The figure for the last twelve months for each Auto-Chemist is printed out together with the total figure. This "history" list will reveal if a unit has any periodic differences in performance.

List number 3

The chemicals that are handled in the Auto-Chemist vary very much in aggressivity. The reliability and failure type is different when the pipettes operating with glykos diluted with water or with concentrated sulphuric acid.

For each component type, Auto-Chemist, month, analyse type and failure type the reliability is calculated. Usually this is given as an MTBF-value. Here the reliability is given as the number of failures per 10 000 component hours. In this list the reliability of every component and analyse type printed out together with the twelve months' average. In order to estimate the accuracy of the figures, the number of component hours that the statistic is based upon is given. By giving the four units that have the lowest reliability (highest figures) for each component type, it is possible to see if the component reliability is mainly caused by one specific unit or not. The unit that has shown the highest reliability (lowest figures) are also printed out to give an idea of the reliability that can be obtained.

List number 4

This list makes it possible to see the correlation between failure type and analyse type. The reliability is given as number of failures per 10 000 component hours. The reason for an unexplainable value in previous lists might be found in list number 4 or 5. The reliability is calculated for every component type and sorted by failure type and analyse type. For example: The analyses TOTAL LIPIDS (TLIP) causes mostly leakage (failure code 20 and 21) on pipette 555 190 003. It can also be seen that only a minor part of the break-downs are found during PM (Preventive Maintenance)-inspections. As the value for failure code 21 is higher than code 20. By comparison with the same value for pipette 555 190 092 it can be determined if this will give a higher reliability.

This list a powerful tool when finding the reason for different component reliability. It also measures the effectivity of the inspection methods to prevent various failures of different components.

List number 5 (not shown)

List number 5 is identical to number 4 in layout and type of information. The difference is that the information is based on one specific Auto-Chemist only. This list is valuable when finding the reason why a specific Auto-Chemist shows a reliability higher or lower than the average.

List number 6

List number 6 is foremost intended for maintainability and service follow-up. For each unit the following values are calculated for maintenance performed by AGA and by the user:

- Total number of actions
- Average waiting time for repair man
- Average repair time on unit
- Maintenance cost - material
- Maintenance cost - wages
- Number of actions on different sub-units
- Meantime to repair (MTTR) for different sub-units
- Total average MTTR-values

This list makes it possible to see differences in waiting and repair times that may reflect the efficiency of different service groups and skill of repair man on different sub-units. The total MTTR value of different sub-units reflex maintainability and will show where actions shall be taken to raise the availability to an even higher value.

6.5 Results

The know-how of the employees of AGA Medical Division combined with this information system and its output lists insures that the Auto-Chemist will have the highest obtainable AVAILABILITY, RELIABILITY and MAINTAINABILITY now and in the future.

7. FINAL REMARKS

7.1 How to organize for M

In the previous parts of this essay we have seen where to find the emphasis on M in the company. Mainly the following departments are involved: Purchasing, design and maintenance. Even if these departments are not managed by the same person - which means that the company has no "Indirect Labor Manager" - it is our experience that M can be managed in a decent way. We feel it is a good example of the more "horizontal" organization or project group thinking now gaining interest all over the world: Persons from different levels and departments in a company cluster together to work on specific projects or to solve specific problems of mutual interest to them where their special know-how and experience can be used.

By this organization structure where M is divided on three departments we have also avoided a very common evolution: A small department grows to a big one without substantially rising its output. This is Parkinson's Law. Instead we prefer a M group with representatives from all the three departments and having scheduled meetings and working against short and long range plans. Committee chairman could be the maintenance manager.

At each department there should be a person responsible for the co-ordination of M efforts within the department and the co-ordination with other departments.

7.2 How to install M

We will briefly discuss the installation starting from a general project implementation model:

1. Pre-studies

   Where to use M in our company? Feasibility. Preliminary costs and savings. Pay-off.

2. Information

3. Project definition

   Goals. Level of aspiration. Time and personnel assigned. Use of outside consultants. Implementation plans. Priority decisions. Costs and savings.

4. Top management decision

5. Implementation

   Work of the M group according to schedules and plans.

6. Follow-up

   Pay-off calculation. Long range plan for further M development in the firm. Follow-up of M activities in progress.

4. 4. 74

MAINTAINABILITY (M)

0. INTRODUCTION CASE

In order to explain the concept of maintainability (increasingly being referred to as M), it is an advantage to give an introductory example.

Consider the two different types of brakes on cars: The drum brake and the disc brake. These two items performe the same task, are differently designed and of different M. To change the brake linings and check function of four wheels takes about 50 minutes for the first type and about 20 minutes for the other. The disc brake is such that it is easier to maintain. We could also express this as a difference in maintainability - i. e.: The equipment repair time (ERT) is reduced.

The concept of M is closely related to reliability (R) and availability (A_n). Generally, the drum brake will function longer or the reliability is higher (50 %) because the time between failures is longer (TBF). Availability (A_n) is related to the product of M and R if other factors are neglected. In this simplified case the value of A_n for the disc brake is better than that of the drum brake, in spite of the lower reliability. This example reflects maintainability as a system characteristic.

1. DEFINITIONS OF M

A general accepted definition of M does not exist but several criterias, requirements and parameters used in context with M can be found. The goal is to have M considered as a design parameter and that M philosophies are considered in future systems development programs along with performance and reliability. Two concepts are connected to M:

- definitions of M
- maintainability index.

Examples of definitions of M in the various US military specification are the following:

1. M definition

Maintainability requirements for air space systems and equipment, definitions of maintainability (generally accepted by all the services).

Maintainability
The combined qualitative and quantitative characteristics of material design and installation which enable the accomplishment of operational objectives with minimum expenditures including manpower, personal skill, test equipment, technical data and facilities under operational environmental conditions in which scheduled and unscheduled maintenance will be performed. Maintainability is effective at all levels of maintenance, as follows:

a) Maintainability (organizational). The capability of an equipment to be returned to an operational status in a specified period of time.

(b) Maintainability (field). The capability of an equipment to be returned to a serviceable status with specified test and repair equipment within a specified period of time.

(c) Maintainability (depot). The capability of an equipment to be overhauled and returned to a serviceable condition at a specified percent of unit cost.

2. Maintainability for shipboard and shore electronic equipments and systems.

Maintainability requirements. The procuring activity will specify an equipment repair time (ERT) in the detailed equipment or system specification.. The design of the equipment or system shall be such that the geometric mean of all active repair time intervals required to repair independent failure shall not exceed the specified ERT. Complience with this requirement will be verified in the final design stage and in the pre-production and production stages.

The first definition of M is qualitative and related to the maintenance system. The second is quantitative and more closely connected to the design and the repair time.

Maintainability index definition

A quantitative figure of merit which relates the M of an item to a standard reference.

2. M IN RETROSPECT

The historical background of M is nearly only a military story. In 1961 around 25 % of the United States defence budget was maintainance. The more complex an equipment is - military and commercial - the more new types of engineering problems concerning high performance, reliability and maintainability turn up. In the Post World War II period, particularly because of missiles, research. and maintainability problems needed a lot of problem solving capacity.

Maintainability and maintenance requirements were generally referred to as a "best effort" item. No criteria was specified and contractors were free to interpret contracts as they liked. Action by the United States Department of Defence directive (DOD) and others have culminated in a number of specifications on maintainability and the maintainability approach is quite different. Each military service has now requirements for maintainability. Two of these are mentioned under the sub-title definitions of M.. A military application of M for a missile system on ready status is presented. Demand can come at any time. For any given system (and generally its dependent functional sub-system) a "demand" profile can be derived from the overall mission.

Certain limitations exist on the maximum number of failures per unit of mission time and the maximum tolerable down-time per failure. If these limitations are not exceeded the system can fulfill

2 OF 2

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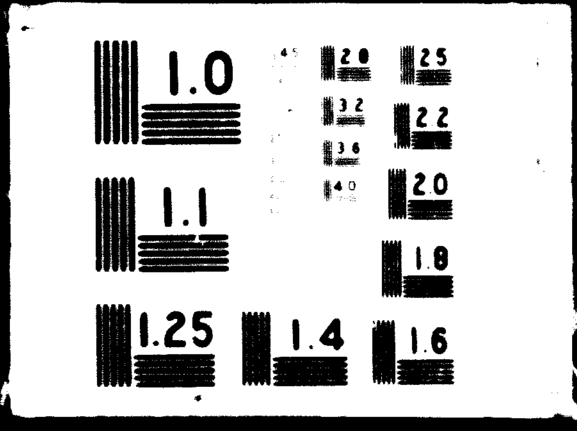

REFERENCE LIST

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   Goldman, Slattery
   John Wiley & Sons Inc., London
   1964

2. ELECTRONIC MAINTAINABILITY

   Ankenbrandt
   Eng. Publ.
   Elizabeth
   New Jersey
   1960

3. DESIGN, METHOD

   Gregory
   Butterworths, London
   1966

4. MODERN PRODUCTION MANAGEMENT

   Elwood S Buffa
   John Wiley & Sons Inc., London
   1969

LIST NO 1

PERFORMANCE FOLLOW-UP — NUMBER OF MAINTENANCE ACTIONS PER SUB-UNIT

AUTOCHEMIST	AVAILABILITY		LOST ANALYSIS/DAY MAXIMUM		LOST ANALYSIS/DAY AVERAGE		UPTIME		DOWNTIME		TOTAL	MAINTENANCE COST MATER		MAINTENANCE COST WAGES	
NO USER	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	RUNNING TIME	LAST MONTH	AVER.	LAST MONTH	AVER.
1. ABC MED.CENTER	972	953	725	300	100	[illegible]	[illegible]	[illegible]	42	18	13450	600	500	513	[illegible]
2. X-TOWN HOSP.															
TOTAL	951	982					[illegible]	[illegible]	[illegible]	22	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

AUTOCHEMIST	NO OF MAINT. ACTIONS		PIPETTE		[illegible]		SUPPLY		[illegible]		[illegible]		[illegible]	
NO USER	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.
1. ABC MED.CENTER	[illegible]	151	[illegible]	[illegible]	22	31		[illegible]	[illegible]	11	[illegible]	[illegible]	[illegible]	[illegible]
2. X-TOWN HOSP.														
TOTAL	[illegible]	[illegible]	41	[illegible]	[illegible]	[illegible]	[illegible]	10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

AUTOCHEMIST	[illegible]		AMPLIFIER		POWER CONTROL		[illegible]		[illegible]		COMPUTER	
NO USER	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.
1. ABC MED.CENTER	[illegible]	[illegible]	[illegible]	11		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2. X-TOWN HOSP.												
TOTAL	[illegible]	[illegible]	[illegible]	12	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

LIST NO 3

COMPONENT FAILURE FREQUENCY - FAILURES PER 10.000 COMPONENT HOURS

COMPONENT	ANALYSIS	STAT BASE COMP.H.	LAST MONTH	AVER.	USER - FREQ		USER - FREQ		USER - FREQ		USER - FREQ		USER - FREQ		USER - FREQ		USER - FREQ		USER - FREQ	
PIPETTE 555 190 003	BUN		35	29	4	65	7	45	11	36	1	32	3	7	11	5	31	5	6	2
	BILIR		40	41																
	AKLF		26	20																
	TOT	7354	132	122																
PIPETTE 555 190 092	BUN																			
	BILIR																			
	ALKF																			
	TOT																			

LIST NO 4

COMPONENT FAILURE FREQUENCY PER FAILURE TYPE AND ANALYSIS TYP

FAILURE FREQUENCY = FAILURES PER 10 000 COMPONENT HOURS

COMPONENT	FAIL TYPE	STATE BASE COMP HOURS	FAILURE FREQ. LAST MONTH	FAILURE FREQ. AVER.	AMYL LAST MONTH	AMYL AVER.	URIB LAST MONTH	URIB AVER.	URIC LAST MONTH	URIC AVER.	BUN LAST MONTH	BUN AVER.
PIPETTE 555 190 003	10		41	52	07	11	03	02			01	
	11		13	21	03	05		01				
	20		07	10	2							
	21		32	29	11	05						
	30		13	10	01	07						
	31		0	0	0	0						
	40		23	19								
	41		0	0								
TOTAL		11354	129	141	2[illegible]	23	03	02			01	

COMPONENT	FAIL TYPE	SGOT LAST MONTH	SGOT AVER.	SGPT LAST MONTH	SGPT AVER.	ALPH LAST MONTH	ALPH AVER.	TLIP LAST MONTH	TLIP AVER.	TBEN LAST MONTH	TBEN AVER.	LDHB LAST MONTH	LDHB AVER.	LDH LAST MONTH	LDH AVER.	BIP LAST MONTH	BIP AVER.
PIPETTE 555 190 003	10					02	03					07	10	03	01		
	11					01	01					04	10	01			
	20					05	08	04	02								
	21					05	12	10	08								
	30																
	31																
	40																
	41																
TOTAL						07	11	05	10	01		07	10	03	01		

COMPONENT	FAIL TYPE	ALB2 LAST MONTH	ALB2 AVER.	BILIR LAST MONTH	BILIR AVER.	TBIL LAST MONTH	TBIL AVER.	DBIL LAST MONTH	DBIL AVER.	TP LAST MONTH	TP AVER.	NA LAST MONTH	NA AVER.
	10	01	03					06	03				
	11							02	01				
	20							03	04				
	21							04	06				
	30												
	31												
TOTAL		01	08					08	02				

COMPONENT	FAIL TYPE	K LAST MONTH	K AVER.	CA LAST MONTH	CA AVER.	CL LAST MONTH	CL AVER.	P LAST MONTH	P AVER.	GLU LAST MONTH	GLU AVER.	CRED LAST MONTH	CRED AVER.
	10	03	14										
	11	01	02										
	20							01	01		01		
	21												
	30							08	02				
	31							?2	01				
TOTAL		08	11					04	08		01		

COMPONENT	FAIL TYPE	CREA LAST MONTH	CREA AVER.	CHOLE LAST MONTH	CHOLE AVER.	CHOL LAST MONTH	CHOL AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.
	10	02	02										
	11	01	01					01	01				
	20												
	21	08	06			11	06						
TOTAL		11	08			11	06	01	01				

COMPONENT	FAIL TYPE	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.	LAST MONTH	AVER.
	10												
	11												
	20												
	21												
TOTAL													

COMPONENT	FAIL TYPE	STATE BASE COMP HOURS	FAILURE FREQ. LAST MONTH	FAILURE FREQ. AVER.	AMYL LAST MONTH	AMYL AVER.	URIB LAST MONTH	URIB AVER.	URIC LAST MONTH	URIC AVER.	BUN LAST MONTH	BUN AVER.
PIPETTE 555 190 002	10				01	02						
	11											
	20											
	21						01	02	01			

COMPONENT	FAIL TYPE	SGOT LAST MONTH	SGOT AVER.	SGPT LAST MONTH	SGPT AVER.	ALPH LAST MONTH	ALPH AVER.	TLIP LAST MONTH	TLIP AVER.	TBEN LAST MONTH	TBEN AVER.	LDHB LAST MONTH	LDHB AVER.	LDH LAST MONTH	LDH AVER.	BIP LAST MONTH	BIP AVER.
PIPETTE 555 190 002	10																
	11																
	20																
	21																

COMPONENT	FAIL TYPE	ALB2 LAST MONTH	ALB2 AVER.	BILIR LAST MONTH	BILIR AVER.	TBIL LAST MONTH	TBIL AVER.	DBIL LAST MONTH	DBIL AVER.	TP LAST MONTH	TP AVER.	NA LAST MONTH	NA AVER.
	10												
	11												
	20												

COMPONENT	FAIL TYPE	X LAST MONTH	X AVER.	CA LAST MONTH	CA AVER.	CL LAST MONTH	CL AVER.	P LAST MONTH	P AVER.	GLU LAST MONTH	GLU AVER.	CRED LAST MONTH	CRED AVER.
	10												
	11												
	20												

LIST NO 6

SERVICE FOLLOW-UP — NUMBER OF MAINTENANCE ACTIONS AND AVERAGE REPAIR TIME PER SUB-SYSTEM

AUTOCHEMIST NO USER	REP.BY		NO ACTIONS LAST MONTH	NO ACTIONS AVER.	WAITING TIME LAST MONTH	WAITING TIME AVER.	REPAIR TIME LAST MONTH	REPAIR TIME AVER	MAINTENANCE COST MATER LAST MONTH	MATER AVER.	WAGES LAST MONTH	WAGES AVER.	PIPETTE LAST MONTH	PIPETTE AVER.	FOTOMETER LAST MONTH	FOTOMETER AVER.
1. ABC MED.CENTER	USER	NO	43	32					315	406			10	08	11	10
		TIME					03	02					03	02	01	01
1. ABC MED.CENTER	AGA	NO	05	07					600	500	512	376			01	02
		TIME			17	13	14	12							03	03
2. X-TOWN HOSP.	USER	NO														
		TIME														
2. X-TOWN HOSP.	AGA	NO														
		TIME														
TOTAL	USER	NO														
		TIME											.25	.21	.95	.96
	AGA	NO														
		TIME											.21	.20	.90	.83

AUTOCHEMIST NO USER	REP.BY		SUPPLY LAST MONTH	SUPPLY AVER.	CHEMICAL LAST MONTH	CHEMICAL AVER.	HEATING LAST MONTH	HEATING AVER.	COOLING LAST MONTH	COOLING AVER.	WASHING LAST MONTH	WASHING AVER.	AMPLIFIER LAST MONTH	AMPLIFIER AVER.	POWER CONTROL LAST MONTH	POWER CONTROL AVER.	MECHANICS LAST MONTH	MECHANICS AVER.	MINICURE LAST MONTH	MINICURE AVER.	COMPUTER LAST MONTH	COMPUTER AVER.
1. ABC MED.CENTER	USER	NO	01	01	06	05			02	01	03	02					01	01			01	01
		TIME	01	01	05	04	0		03	01	01	01					01	01				
1. ABC MED.CENTER	AGA	NO					01	02	02	02			03	03	01	02	03	03	01		11	05
		TIME					03	03	03	03			02	05	03	02	01	01	08	13	03	02
2. X-TOWN HOSP.	USER	NO																				
		TIME																				
2. X-TOWN HOSP.	AGA	NO																				
		TIME																				
TOTAL	USER	NO																				
		TIME	1.11	1.06	5.21	5.07			1.65	1.13	0.81	0.72					1.15	0.70	4.21	3.79	2.15	1.63
	AGA	NO																				
		TIME	[illegible]	[illegible]	[illegible]	2.63	[illegible]	2.09	[illegible]	[illegible]	0.50	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.70	[illegible]	[illegible]	4.51	3.75

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