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04830

Distr.
LIMITED

ID/WG.145/9
13 February 1973
ORIGINAL: ENGLISH

United Nations Industrial Development Organization

~~[illegible]~~

Planning and organization

Symposium on Maintenance ~~and Repair in Developing Countries~~

Tokyo, Japan, 12-17 March 1973

AVAILABILITY OF EQUIPMENT

by

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Organised in co-operation with the Government of Japan and the Japan Management Association (JMA).

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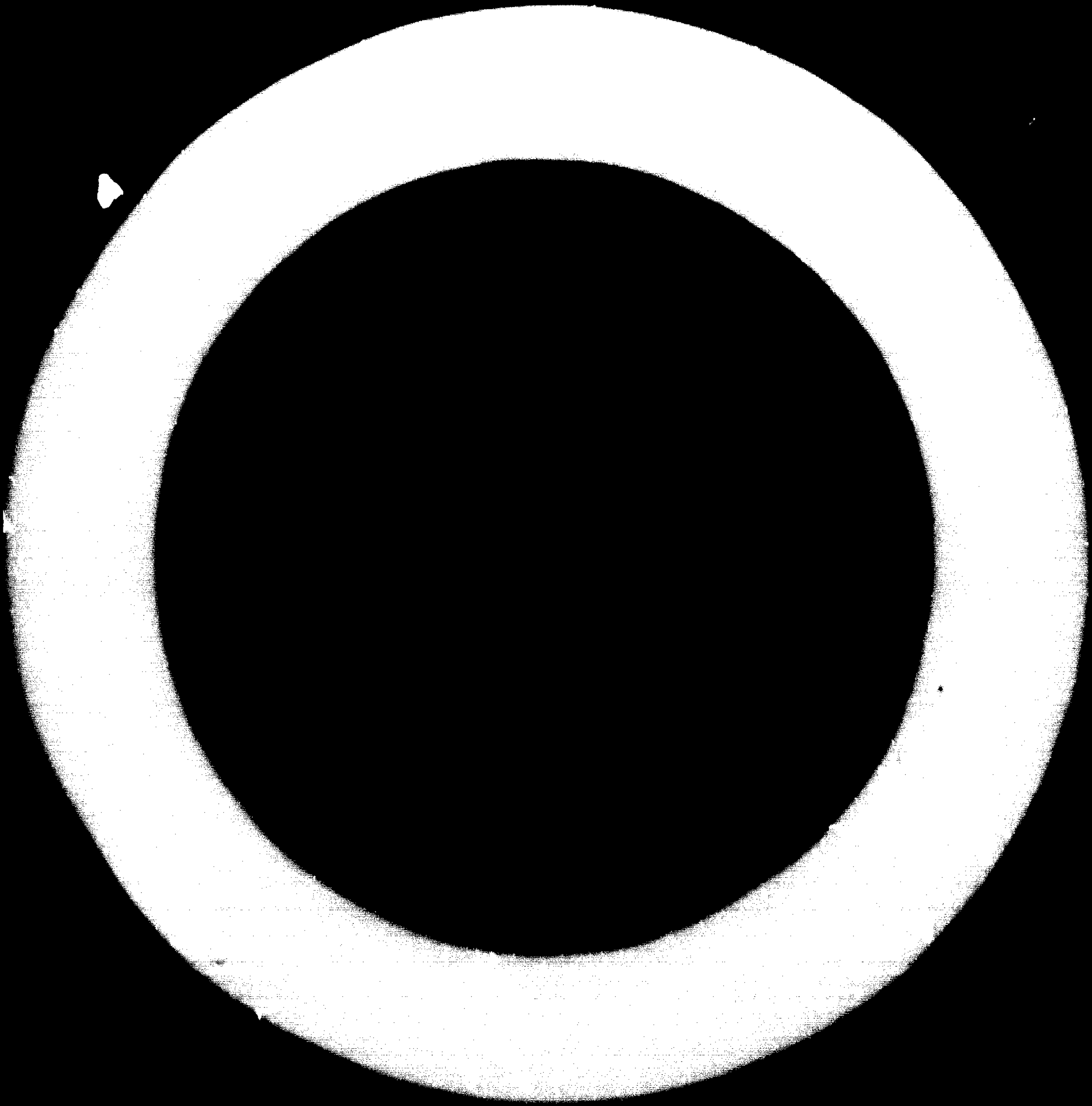
id. 73-960



Introduction

When discussing the conception of availability it is probably fruitful to start by visualizing some typical examples of various pieces of equipment, which we want to have available for their intended use.

We want the aeroplane, the ship, the truck, the steel rolling mill, the machine tool or whatever we have in mind, ready for work, when this would be profitable, i.e. when this would meet a demand from a market to which we can sell the product or the service, rendered by our equipment. And furthermore we want it to keep on doing this work as long as possible or at least as long as there is this market demand.

We want the equipment available for start, when requested, and available for continued work as long as requested. Our equipment must therefore have a certain availability. Before we go into this conception further, we stick for a while to our aeroplanes etc. Let us bring all these together under one common name, which is, and will be, frequently used. All these things are technical systems. When we discuss these systems and look at them from an availability point of view, we apply a combined economical/technical viewfinder to scrutinize their qualities and characteristics, which is called Systems Engineering. The methods used in Systems Engineering have been derived from the field of Operations Research or Operations Analysis, which was built up during and after the last war.

When looking at the availability from the theoretical side it is unavoidable to pay some attention to definitions of the basic conceptions. We will do so but first say some words about why this has to be done. It is not very difficult to design and build even very complex equipment for various objectives. The difficulty is to make this within the limited allowance of resources which we always have to reckon with. And trying that, our objective is to produce the best result possible within our allowance. Therefore we have to consider and compare different possible alternatives in order to chose the one, which gives us the best result within our means. Now, to be able to chose, we must measure, and to be able to measure, we must define measurable qualities or characteristics. It is here, that the theoretical side, the theoretical tools come into view.

The aim of this paper is not to teach the different theoretical tools, mathematical models, etc. which are used. That is not possible and would need much mathematical grounding knowledge and extensive training courses. What we can do, is to look at the basic definitions for the important system characteristics and illustrate how these are related to each other. By doing so, we can get an idea of, what can be done and what has to be done in order to produce the information, necessary for us to facilitate our choice, or - in other words - to give us a ground for the decisions we must make, the so-called decision process, when we purchase our systems, or we design and build them ourselves.

Our systems, illustrated by the various examples of systems, mentioned in the beginning, are meant to produce some sort of products, for instance a "hardware" product, such as rolled steel bars or steel sheets, or a service, such as transport capacity, or a machining job, or whatever is requested. And this product is measured in tons/year, or ton-km/year, or passenger-km/day, or worked away weight of steel in kg/hour. To produce these products, resources must be spent. The products give a known or expected income, which must exceed the cost of the spent resources to make the whole thing possible. Now, we must presume that we know, what we can get in the market for our "products", but what are our costs, and - very important - all our costs? The systems, used nowadays, producing complex products or having a very high output productivity are complex and seem to become gradually more so. That does not necessarily mean complicated, but being built of a very great number of components, mechanical, hydraulic, pneumatic, electric, electronic etc., and being very automized, they - no doubt - get more and more complex. And complex systems cost much to procure, to install and to operate.

The investment costs, for which we use our earned money or we borrow money in the bank or are allowed money from the government, are costs for, mainly,

- the development work for new design,
- the design work itself,
- the construction or building,
- the commissioning,
- the initial training, and
- eventual surrounding service installations.

After the commissioning - which is a word for setting the system in operation with possible starting difficulties, "teething troubles" or "children's diseases", - the operation period or production period is expected to bring in the money to pay back the investment cost as well as to pay for the running operation costs. These are costs for resources spent into the production such as

- operator's man hours
- raw material
- power
- continuous operator's training

and costs for activities to keep the operation running, such as

- planned, preventive maintenance
- corrective maintenance, in case of failure
- downtime costs,
- renovation, big overhaul from time to time,
- modification for improving the system, if proved necessary
- continuous maintainer's training.

The costs fall out during the lifetime of the equipment from the start of the development work through design, construction, commissioning and operation to decommissioning for selling or scrapping, principally something like the diagram in Figure nr 1, whereas the income turns up only during the operation period and then has to pay - by depreciation and interest - also for the investment cost. Thus, the total coct per each produced product item during the total lifetime must be paid by the total mean selling price.

Some comments seem logical to make here, even if they have little to do with the availability aspects. The total selling price must, of course, also pay for the overhead costs, but, and this is important, these costs must cover a margin to allow for developing the production methods, in order to make it possible to keep abreast with the actual technology.

The price also must give a margin for risks by unpredictable market surprises and suchlike. The remedy for this is to request that the new equipment is paid for in a limited number of years. Policies here in the industrially developed countries seem often to vary in the area of 3 - 6 years.

Even if the costs for the products are not paid for by the consumers, if f.i. government railways or other transport means are paid for by the government and the tickets do not go half way to pay back the costs, it is very helpful to calculate in terms of total lifetime cost per product item and to have an idea of what a market price would have to be. By doing so it is possible to do suitable comparison calculations to find out the best alternatives for spending money in order to attain certain defined and specified objectives.

Minimizing the costs

If we now, after this introduction look closely at the task to minimise the total cost, it should be obvious, that it is desirable to know the operation cost fairly well already at the procurement stage, and in fact already at the development or projecting stage. When the detail design starts the contract is generally already concluded. This means, that the buyer already has decided on which supplier and which design is to be used. The buyer then must rely on the supplier to deliver a system, the operation costs of which in the future do not exceed what is economical. So the buyer has to rely either on the suppliers good name and reputation, or on proved experience from earlier deliveries, or he must make the supplier prove his promises in some way or other or, lastly, to take his own responsibility and not blame anyone else, if later the operation shows to be more expensive than anticipated.

Why do I stress the part of the supplier so much? Does he not just have to deliver a system that can produce the correct products in the correct number? And leave the question of the operation cost to the buyer/operator? No, this is the central point in my conception. The operation cost is to a very large extent built into the system by the designer. And when once the design is decided upon, there is not much to be done afterwards to change the situation, unless of course, the owner is prepared to pay heavily for modification of the design or even more heavily later for modifying the equipment itself. There has been suggested, based on experience mainly in the electronic equipment field, but probably with significance also in other fields, that if the cost for a modification of the design, after the contract is concluded, in order to lower the operation cost, is represented by the number 1, the following series of numbers is valid for the same gain in bringing down the operation cost by measures at the different development stages of a certain system:

0.1	Project stage before contract
1	Design stage after contract
10	Building stage before delivery from supplier's workshop
100	Assembling stage at the buyer's before commissioning
1000	Operation stage after commissioning.

This seems a bit diagramatic, but probably in most cases it does not deviate much from the true reality.

So, when buying technical equipment, do not ask for the lowest bid, ask for the lowest "life cycle cost" or "ownership cost". And it is here that the difficulties come into the problem. How high are the operation cost part of the "life cycle cost" during the years to come? Well, it is for these questions that the System Engineering has been developed. It is no witchcraft formula, that can solve our problems just by a stroke. It takes much boring work. It is applied mainly at the project stage and deals with the cost for different alternative investment measures in order to bring down the operation cost. The technique comprises different methods to predict the gain in raised availability and lowered operation cost by undertaking defined suggested measures, which might raise the investment cost. Of course generally it costs more to procure a good reliable plant than to buy just a plant. The questions are: How much more? And: How much better plant? And both questions answered in plain monetary terms.

The work consists of comparing cost for investment and operation for all alternatives, found worth while to evaluate. And of course also of comparing anticipated availability - how much work do we get out of the machine? To underline the importance of this we can as an example consider just one production unit. Obviously in such a case the availability is deciding for the income side of the calculation. If we risk a low availability we must perhaps consider a spare unit to be sure to keep up the requested production. This is an investment item, taking us back to the cost side. Obviously spare production units comprise an alternative, to be evaluated, compared to the alternative with a lower number of units with higher availability.

The System Characteristics

To structurise our cost-benefit-problem, let us take a look at those characteristics of a system, which are decisive for the result. Generally they are defined as is shown in the Figure 2. This diagramatic description is a generally valid model of a system, but concentration on those characteristics, which are specially relevant for the operation economy problem.

The diagram is to be understood so, that the system is expected to accomplish an overall mean total production rate or productivity, an Operative Performance. To do this the system must accomplish a Technical Performance, which is the productivity or production rate, provided no failures or hindrances whatsoever. The system also must accomplish a Reliability Performance which is the extent, to which the system can work at this productivity rate. It cannot work continuously so. The production is set down below 100 % by failures and repair and by necessar preventive planned maintenance work, which necessitates the system to be shut down and taken out of operations from time to time. For how long depends on a number o conditions, often rather difficult to define and to measure. To make us able to handle often complicated reality by mathematical methods or even just to understan the real problem we make a simplified picture of the reality to facilitate our understanding. We make a model, Figure 2. That is to say, that we simplify reality to a certain extent and exclude or consider as constant such factors that are not necessary to define in a certain problem situation.

This Figure 2 is meant to be read so, that the "front" squares indicate names of the real system characteristics, whereas the "back" squares indicate the corresponding model characteristics. For the model characteristics we use measures, possible to work with in mathematical symbols. So f.i. the technical performance is the production if no failures occur but still under influence of various envi ment conditions more or less known and more or less possible to define correctly, and the influence of which on this performance is not exactly known. To make us able to work in a model we have to define the model characteristic Capability, which is the production rate under constant and specified conditions and provided no failure or even failure risk exists. In the same way the Reliability Performa is the rate at which the production can be kept at the defined capability taking into consideration the eventual failures and the necessary time to correct these and also the time it takes to carry through the necessary inspection routines and generally preventive maintenance. All sorts of conditions weather, personal, eve political, can set down the production. To be able to speak of a model character we must presume that we have constant and defined conditions of operation. One o the model characteristics, most widely used for this is Availability and that is the proportion of time during which we have the defined capability. It can be expressed alternatively as a probability figure, saying that during a certain period of time with that probability we have the system working at this capability. Or, in case we deal with a starting availability the number of successful starts we have out of 100 trials, which is equal to the probability measured in percents, that the system will start on trial.

The Reliability Performance, or in model terms, the Availability depends on three model characteristics, as shown in Figure 2. At what rate or risk does failure occur? To be able to say anything about this, we must define, what sort of failures we speak about. Is f.i. every occurance, when we have to change an electrical fuse or a lamp bulb, a failure and an action of corrective maintenance? Or is it just a part of the operation? How severe does an occurance have to be for the production, to be defined as a failure? Is it usually spoken of

- failures, that totally prevent the production or the function,
- failures, that deteriorate the production or function to a certain degree or to a lower quality, and
- failures, which do not - at the moment - affect the function, but can wait until next planned stop.

It is obvious, that we can speak of a certain Security of Function, measured in f.i. probability of failure or number of failures per 1000 running hours or mean time between failures, MTBF, only if the conditions, under which the system is working, are constant and defined and can be measured. Constant conditions, which are known and defined, is a base for the model conception.

In reality the conditions are not constant and, not always known, especially in the future, where they have to be anticipated with a certain security, when we try to predict the operation costs. Still they have to be anticipated by the designer and for the future owner/operator who has the task of economic operation during the years to come. So the more knowledge we have available of operating conditions and failure risk the better.

The Security of Function is one of the characteristics, which belong to the technical system itself. The name of the characteristic, used here, is not commonly used. Very often the word Reliability is heard of. This word however is often used also for the overall security-of-operation characteristic, see Figure 2. It is somewhat confusing with "Reliability" in two capacities. Therefore, the expression "Security of Function" is chosen here. One other thing. For this characteristic we do not have different expressions for the real characteristic and the model value, corresponding to "Reliability Performance" compared to "Availability". So we must know when we talk about the one or the other.

The other important characteristic of the technical system, Figure 2, is the Maintainability, important enough to justify two separate papers in this conference. Also here we have the same name for the model value and the real value of this characteristic.

The Maintainability can be defined as the suitability of the system to become repaired in cases of failure, or the adaption of the system for maintenance. It depends on all such things, that facilitate or delay the maintenance job such as easiness to inspect and localize a defect by f.i. operation condition indicators or by inspection hatches. Other such measures are building the system in modules, easy to disconnect and exchange, or generally the easiness to dismantle and re-erect. Sometimes one finds also such things as specially designed tools and specially made up instructions for the job defined as measures to improve maintainability.

What we want - which we do, in the system engineering field - to define exact measures for this characteristic we must have a model version. This version must be defined as the amount of job to make a certain maintenance action or all necessary actions during a defined space of time. It is measured f.i. in the time it takes or the number of manhours or even the cost and provided that the necessary maintenance support is at hand. This means all tools, instructions, spare parts, skilled people, etc. To be able to talk of the model characteristics and to have an adequate measure of this, only such factors as belong to the system itself are taken into consideration. All surrounding factors, which consequently belong to the organization, must be considered as constant and of adequate quality, and so excluded from influence on the job time.

If the surrounding factors vary, which indeed they do in real life, they influence the time for the job. Therefore, we must necessarily collect such factors which belong to the surrounding organization under a heading. See Figure 2 again. Here is used "Maintenance Efficiency" or alternatively "Support Efficiency". To be able to speak of a model characteristic, this must be defined in a way to allow for representation in figures, which can be used in comparison of alternatives, in f.i. the time to wait for the work to start after a failure has occurred. To give such comparison significance, the factors not belonging to the organization, which influence waiting time or the resource spending for a job, must be considered excluded from influence, be considered as constant.

A few more words about how these system model characteristics are related to each other. The higher they are the higher the availability, that is obvious. But the higher they are, the more expensive they are. Not necessarily always, but mostly. Availability costs money. How much do we gain in availability - and consequently in promoted production - for a certain spending on raising these characteristics? Well, that is for the systematic project work to find out. Generally it can be said though, that if these characteristics are balanced towards each other so, that if a certain spending on either of them gives the same result in raised availability, we most probably have a good design alternative. If we gain considerably more in availability for spending a sum on one of them than on the others, we should certainly do so.

A simple example might illustrate this discussion.

Example: A machine

Security of Function	**Mean Time Between Failures**	**MTBF**	**100 hours**
Maintainability	**- Mean Time to Repair**	**MTTR**	**10 hours**
Maintenance Efficiency	**- Mean Waiting Time**	**MWT**	**2 hours**
Availability	**- Mean Down Time**	**MDT**	**12 hours**
	- Availability	88/100	0.88

Alternative measures to improve availability:

1. **MTBF Raised**

for £ 1000 **to 200 hours**
Availability **188/200** 0.94
\+ 6 %

2. **Maintainability Raised**

for £ 400 **to 5 hours**
Availability **93/100** 0.93
\+ 5 %

3. Maintenance Efficiency Raised

	for £ 10.000	to 0 hours	
	Availability	90/100	0.90
			+ 2 %
1 + 2	£ 1.400	193/200	0.965
			+ 8.5 %

How much is gained by the raised productivity? Does it pay?

Reliability design

Further on a more detailed discussion about these characteristics, which build up the availability, will be presented. Before that is done however, a brief introduction into the System Engineering ways to attack the problem will be useful.

The system consists of "hardware", a number of material parts, which are built together according to a defined structure. These parts function together to give the system the intended total function, needed for the requested production. Therefore, we say that a system consists of a nucleus, material and structure, and a function. The nucleus can, according to the structure, be broken down further into parts, sub-systems of lower order and finally into what we call components, the smallest parts practical to deal with in the actual problem of availability. It can be f.i. pumps, electric motors, etc. Of course a pump can be broken down into casing, shaft, impeller and bearings, but let us for the time being leave the question of the lower limit for this breaking down of the nucleus. In the same way of course the function is broken down into sub-functions etc. down to the functions of the components. This system conception will be dealt with further later on. Let us so far illustrate what we do by Figure 3.

We call this way of breaking down the system nucleus and system function hierarchical. It is obvious that a certain sub-system's sub-function must add value to the system function if the sub-system is worth its cost. We evaluate the security of function, the maintainability and the required maintenance efficienc for each sub-system and consequently also the availability of this sub-system. The availability of the different sub-systems in our system should be balanced. We compare them, evaluate them if possible in money terms or in terms of availability and find out if any of them mean a weak spot, worthwhile to attend to for improving.

After these general statements let us have a look at the traditional reliability design methods. If a number of components are connected into a sub-system for combining their functions into the sub-system function they can be connected in series or in parallel. (This is a model picture, where we use the electric terms). See Figure 4.

When sub-systems are connected in series it indicates that their functions are necessary for the system function. If they are connected in parallel it indicates that their functions can be substituted for each other. In the same way, the function of a group of components parallel to another group indicates, that these groups can be substituted for each other.

If we have a series of components with (by laboratory research or otherwise) known security of function, expressed as probabilities, we can by known mathematical tools find the security of function for the group. See Figure 5.

As each one of p1 - p4 is below 1.00, obviously P is very much so. To have a reasonably acceptable value of P for a long series as often in modern electronic equipment, each one of the components must have a very high value of p.

If we have a number of components connected in parallel, still with known values for security of function, expressed as probabilities, we can find the security of function for the group. See Figure 6. This shows that the security of function is raised considerably by inserting spare units or using sub-systems as substitute for each other. By using mathematical tools of this kind, it is possible to analyse a system. It is possible to work, so to say from top to bottom, from reasonable requirements for the system to work down to find requirements for the various components to achieve the requested result for the system. It is also possible to work from bottom to top. If we know or find out the characteristics for the components we plan to use, we can by calculation find out the resulting characteristic which we reach for the system. In working with real problems we have to combine these approaches and work up and down the ladder until we feel satisfied. We might f.i. know the characteristics of most of our components and our sub-systems. We want however to modify or modernise by using a new design with improved function for some sub-system or other. By working along the lines, very briefly indicated, we can establish the security of function, the maintainability and the maintenance efficiency necessary for this sub-system to attain the overall system availability requested.

It is important for the resulting system reliability that the components have good qualities, have a high security of function. That should be obvious from what is said. I will come back to the component question later under the heading "Components". Here however I will end this section by stressing the fact that the structure, the way we build the components together, is very important as well. If f.i. some components are not as reliable as we would like, we can connect spare ones in parallel and thus attain a higher availability of the sub-system in which they work. If it is not possible to insert parallel units, we can build them easily exchangable and have spare units at hand and good facilities and a high preparedness of the maintainers to locate the failure and to change for new ones. This is to compensate the lower security of function by higher maintainability and maintenance efficiency. This might be more economic than to raise the security of function of the first ones or to add permanently connected parallel ones. And of course, in some applications the only way.

System Characteristics. Some Details

It seems appropriate at this stage to discuss more in detail the system characteristics.

Security of function, (often called reliability with some confusion as a result) means, as stated before, the ability of the system, sub-system or component to work as requested without failure. It can be stated as the adaption of the design against risk for failures. It can be measured in mean time between failure, or probability for function, or inverted probability for failure. Such values must be stated under defined conditions of service or operation, as such environment factors can influence the risk for failures considerably without this being attributed to the system design itself. Such conditions can be temperature, air moisture and cleanliness, load variation, vibration and shock, operational mistakes, overloading, bad maintenance not up to the prescribed standard and various other things. So obviously to make our predictions about reliability come true we must try to keep such conditions during the operation stage at the stated standards. This takes a lot of instruction and training and accepted responsibility for the production result. It also takes much of routines, fixed down to details to avoid overlooking small but important factors. This will however no doubt be dealt with in the later papers giving the practical application aspects.

The maintainability, the characteristic of the system to be suitably adapted for the maintenance work, is extremely important. Having a considerable influence on the availability, it will be dealt with in two papers to follow, so I leave it out here.

The Maintenance Efficiency or Support Efficiency, the third decisive availabilit factor cannot be defined strictly as a system characteristic, if we define the system as we have done up till now as the technical nucleus with its function. If so, it belongs to the surrounding environment. We must still define it as a real characteristic: the suitable adaption of the organization to the maintenance work requested, and as a model characteristic, with this adaption measured in such measures as f.i. waiting time after a failure has occurred until the repair work starts, or the cost for keeping up the necessary attention or alertness for attaining a certain maximum waiting time. It can also be expressed as waiting time plus repair time, provided the maintainability of the technical system is defined and constant, and so does not influence the repair time. If we express this characteristic as cost, it is of course not very often possible to allocate the maintenance organization costs to each separate technical system of the enterprise, which is under the responsibility of the maintenance organization. Some of the cost items though could be possible to allocate, such as cost for special spare parts, special tools, specially skilled people, maintainers on watch for eventual failures if these are specially directed towards specified systems.

Components

It should be obvious now from what is said under "Reliability Design" that the quality of the components of the system are of decisive importance for attaining a certain reliability of the System. Of course the structure, the way of building the components together and let them function together also is of a decisive importance. That was dealt with under the heading "Reliability Design". Here we will limit the discussion to the components and their characteristics.

First: What is a component? We touched upon this question earlier under the eading "Reliability Design". Do not let us be too logical or theoretical here. et us be practical and pragmatic and say: The components are the basic units of a ertain system design, which are not practical to break down further, because we know or can achieve knowledge of these basic units as they are. They do not have alternative designs, are often standardized and can be procured in the market. Examples: a small standard electric motor, a ball bearing, a hydraulic valve, a gear box. Of course technically, these can be broken down further, the motor in armature, bearings and stator, the gear box in different bearings, shafts, gear drives and gear wheels. However we would probably not get any better knowledge about security of function of our basic units to be used for our reliability calculation by this further breaking down. Furthermore, we would probably never pick these apart for repair in case of failure but exchange them as units for spare. They are obviously not of interest for maintainers, economically or technically otherwise than as units. So let us stop the breaking down with these and consider them as our components.

Let us now discuss some different types of components from a reliability point of view.

In the electronic field these ways of handling the reliability problems have been developed originally for several reasons. Firstly it was necessary. The electronic techniques allowed for very complex and intricate equipment. Think of radar, computers, radio, telecommunication generally. Electronic solutions need ver many components in series. These must have very good and also very well known characteristics, if the resulting characteristics of the system would meet any reasona requests. So it was necessary. It was however also made possible, because the electronic components in most cases could be fairly well known by research and development work, which did not cost overwhelmingly much compared to the total amoun of money involved. Specially the military applications have taken a lead by all sorts of communication and fire control equipment, by equipment to lead missiles, even by the "moon transport service" developed by the NASA organization in the USA. Further these components can be to a great extent built into "black boxes", in whic the environment, air moisture and cleanliness, temperature, vibration and others can be rigidly controlled. Or the other way round, the laboratory research and development work can rather well simulate the real conditions of the practical applications. All in all, these reliability design methods are not generally applied for all electronic equipment and are gradually more and more used for controlling, automation and information purposes in all sorts of technical branches. The automation and mechanisation that gradually have rationalized industrial proces transportation and all sorts of human life is made possible by electronics. It is natural therefore, that the other part of the equipment, the electric and mechanical machinery, which is controlled by the electronic equipment, has come into focus for the reliability interest. Much work and much thinking and discussion is going on and much is so far achieved to apply this technique to all technical branches and to all sorts of equipment.

So we come down to the mechanical, electric, hydraulic, pneumatic and other components. Can the security of function and the maintainability of these be found, be relied upon and used in the same sort of calculations? Well, the general idea now is, that could we just predict the security of function for these components, we could apply the same technique and we could find out with reasonable security the future operation cost for all equipment and we would know very well, what we were doing and avoid many unpleasant surprises.

Well, why don't we? Mostly the opinion held for this is, that we don't have the same possibilities to achieve knowledge of these components. We cannot as easily simulate the operation conditions in the laboratory. We cannot as easily control the environment for many of the components. We cannot build them into "black boxes", where we shelter them off from vibration, shock, load, moist air, polution etc. Look at electric motors, generators and apparatuses in switch boards f.i. Or look at all sorts of valves, pumps, other hydraulic items as controllers, relays and motors, look at bearings generally.

Some system engineers hold the opinion, that now we are in the same situation for other than electronic equipment; as we were 10 - 15 years ago for the electronic. That then we just had to design the equipment with the aim to achieve a high reliabili which meant: Find the characteristics of the components, build them together with spare units attached, easily exchanged. Design the components themselves with very high reliability. Here the new semi-conductor technique came in very handy. Consequently an extremely high effort was spent to develope this technique. The result was not only the very small components, it was also the very high security of function, the possibility of integrated circuits, which meant building several functions together into "cards" easy to apply as built-in spare units, and easily exchangeable. If we now look at mechanical components we find f.i. ball bearings. Of these we know a lot. We can look up the typical characteristics in the supplier's catalogue.

The reason for this is, that they come in very long series, they are consequently very rigidly standardized, they can be tested by research and the applications can be simulated in the laboratory and the conditions in the real application can be very well controlled by an intelligent system design. If the ball bearing is not exposed to excessive load variation, vibrations etc. which can be done with available technique, if the right sort of lubrication is applied and they are sealed off from pollution, which also can be done, it is possible to predict fairly well how many working hours they will stand up, before they have to be exchanged for new ones.

So, if the system engineers finds, that certain parts, sub-systems or components are vital or critical for the system function, he has ways to approach his problem and suggest measures. Chose well known standard components. Seal off from disturbing factors. Insert redundances. See to it, that they are easily exchangable. More of this will be presented in the papers to follow about maintainability.

See to it that a suitable maintenance organization quickly takes any failure on hand and does the right thing immediately, see to it, that this maintenance organization does a good, effective planned inspection in order to make the right thing, if possible before the failure happens.

Now, perhaps this seems rather easy. Still, there are so many new components introduced in the market, so many new systems with very attractive capability figures, where also well known components come into new applications.

So many designers want, what is generally known as Data Banks, collection of data of all sorts of components, where one could just ask for data for all the components, which are alternatively considered in a certain system design. Such Data Banks are available for electronic components, where data are published about f.i. mean time to failure or mean life provided the component is exposed to a specified lead and specified conditions generally. Why can we not have the same for other components? Well, the reasons are the same as have been given as reasons for the difficulties generally for reliability prediction work. The matter is discussed eagerly at the moment in various circles, some collections of data are available for design work and eventually we will have data officially available for many rigidly standardized components used in standardised applications. Probably however, we will sooner have what might be called Reliability Centres where it would be possible to get system engineering service for suppliers and buyers of complex systems. These Reliability Centres would of course have access to such data banks, which might be available for various technical branches. Such Reliability Centres would be in need for their work not only of data from available data banks, they would be as well in need of data supply from all available sources and would probably work hard to utilize these sources for data for completing the banks as well as for their job at hand.

One of the sources for attaining such data is laboratory work. This means testing the component in a simulation of the application as true to reality as possible.

Next source is prototype work, where the system or sub-systems is tested in a real application, which is operated for testing and development purposes.

The third source is the real life itself. By an intelligent systematic collection of experience data from systems in operation, very much valuable information can be collected and processed to give design foundation. This is done to a very great extent in military organizations. It is also done in large industrial enterprises where much equipment is in operation and the maintenance budget is heavy. This is however not so easy. If we order all experience to be noted down on forms, which is felt to be of value to get to know what really has happened and why a certain sub-system suddenly failed, this filling in of forms would be a very heavy job, which either would not be done or would be too expensive. If we take in a very thin flow of data, possible to collect without too much difficulties, we would perhaps not get to know what we really need. The best balance between these two extreme alternatives is yet to be found, but it <u>has</u> to be found. Some very good applications are working and have given good results. Much development work is going on. Some difficulties lie in the fact that data is collected from the operation of the system for several different reasons One is this reliability data collection purpose. One is the collection of economical data to control, that the work is proceeding according to the production budget. Yet another is to collect all the information, that is of importance to plan the maintenance work. These different purposes set somewhat different requests for the information data collection system. Also here the correct balance between and combination of the various objectives has to be found. We find a combined interest between the financial, production and maintenance departments and the organization for projecting and design of new equipment.

The System Concept

We leave now for a moment the reliability design and component questions and take a wider look around. I have been talking much about systems. A System Concept, a way to model the system, independently of which technical branch is considered, has been developed and published. It is in various circles felt to be of great help when going into one's problems to structure and define them and so facilitate the finding of the solution.

Under the heading of Reliability Design it was stated, that the system consists of a

nucleus:

material **elements** built together and interacting according to a **structure**,

and a **function**,

aimed at fulfilling a specified requirement or reach a specified objective.

The elements are all needed within the system in order to achieve the functional output. The structure defines how these elements interact in space and time i.e. how they are connected and intended to work together to achieve the function. By inflow of resouces into the system, this produces a product according to a defined objective.

Another necessary feature in system analyses and system identification is the concept of system environment surroundings and of the corresponding borderline between the nucleus and the environment. Let us illustrate these facts by Figure 7.

With reference to this Figure we can venture this

Definition: Factors, that belong to the system, are by definition under the control of the analyst in the sense, that he can add or subtract quality and quantity to or from the function by the control of resources.

And: Uncontrollable factors or factors considered or deliberately chosen not to be under control belong to the system environment.

The description of the system is an incomplete model of the reality. This is always the fact, when describing a complex reality. The degree of violating the reality is deliberately chosen to make the model suitable as a tool for studying the actual problem. The analyst describes by the model the characteristics of the system, important for the analyses, and does this in such a way as to express, how the function is generated by the nucleus under inflow of resources and under the uncontrollable influence of the environment. The value of the resources, absorbed in the nucleus is the system cost. This cost can depending on circumstances mean different sorts of resources such as investment cost, operation cost, life cycle cost etc.

The value of the function in relation to the required output is characterized by a measure of effectiveness. A certain effectiveness corresponds to a certain cost of spent resources.

The procedure of evaluating cost and effectiveness and their relationship is called cost-effectiveness analyses.

Referring to Figure 8, a system, defined as we have done here, has these important characteristics.

1. The system is identified by reference to elements, structure and function.
2. The system can be evaluated in a way consistent with its identification i.e. in terms of value of a function and value of resources consumed by the nucleus.
3. The system can be designed by a procedure, that combines evaluation of function relative to objective with allocation and evaluation of spent resources.

The identification of the system nucleus can be done by a successive identification of sub-systems in a way that is indicated by Figure 3. The system is thus identified by a hierarchial breaking down of the system function and the system nucleus.

In order to maintain the evaluation and design characteristics of the system, point 1, 2 and 3 above, the sub-systems must have the same characteristics, see Figure 9.

An Effectiveness Model

Effectiveness generally is a measure of system value. Cost effectiveness analyses is a decision-making tool. The distinct meaning of effectiveness as well as cost can vary, depending on such things as the systems under consideration, the alternatives under evaluation and which measures are best suited to the values in question, etc.

Here it is interesting to introduce another aspect. In the discussion so far I have not mentioned the fact that the characteristics of the system can vary. The system can work in different condition states. It can work f.i. with reduced capacity because of a certain failure, which has demanded the use of a redundancy. It can have several defined system states, which can be utilized according to a known or predicted pattern. The environment can as well have a number of defined states, which also are valid according to a predicted pattern. These patterns represent a system dynamics and an environment dynamics. To those familiar with mathematical terms these dynamics can be represented, "modelled", in a matrix or as vectors.

For each system state and environment state a certain cost-effectiveness relation (Figure 8) is valid.

The sketches of models, shown so far, have not demonstrated these dynamic properties of the system and the environment. A model which illustrates these in a diagrammatic way is found in Figure 10. This model is introduced in the literature by Hans Ebenfelt and Robert Holmqvist (Reference nr 1).

It is the intention of the model that the static capabilities are those, valid under each pair of system and environment states, whilst the system and environment dynamics represent the pattern for these variations, the "dynamic vectors". The effectiveness represents the mean capability during the considered space of time, which can be any from lifetime down to any small period of operation time, which is of interest to study, provided the patterns for the dynamics are known or predicted during this period. One example of application of this concept is given in an Appendix. This system concept can be applied already for methods to define and structurize a complex problem, where complex technical systems work in a varying environment. By using this method it is possible to isolate and define those systems and functions, which are of interest to study and those environment factors, which have a significant influence on the system's capacity. This has been done in a large work, made for the Swedish Shipowners Association, with the objective to find out in what way and to what extent the terotechnology function has significance and how manning and maintenance of the ships should be organized around 1985. The prerequisited are given by a number of prognoses and judgements about the sea trade and the technological conditions in the near future. Among other tasks the study has covered the structuring of what has been called the shipowner system with its function in the system hierarchy above the operative ship system down to the different sub-systems of the ship, relevant to the maintenance system.

The concept, applied for f.i. a production unit, producing some product for a market, fluctuating in product demand - quality and quantity - as well as in price, would lead to a problem structure like the following: The market has a number of defined states, of which each would lead to a certain gross income for sold products.

The production unit, the system, has (in a simple example) a number of system states such as f.i.:

- full production capability,
- limited production capability due to a certain redundance, engaged after a failure,
- out of service for planned maintenance,
- out of service waiting for and under repair of a failure.

The probability that the unit during a certain time period will be in any one of this states, estimated or calculated according to available reliability techniques represents the system dynamics. The probability that the market will be in anyone of the different defined states during the considered period represents the environent dynamics.

The net profit in each pair of states can be estimated or calculated and repreented in a matrix. A matrix or vector calculation gives the mean net profit during he period. The mean net profit corresponding to each separate market state can lso be found, constituting the maximum and minimum amplitudes of the profit. The ariations in difference between production and market demand can form the basis or dimensioning a stock of products, which can be a sub-objective of the study.

Demands for limiting such a stock can on the other hand be constraints in the problem solution. If we find the mean net profit and the fluctuations according to different market states during a number of successive significant time periods, - provided it is possible to estimate the system and environment dynamics during each period - the result is a series of net profit figures, which in itself represents a dynamic course of events.

Applying this concept could be one way to estimate the economical life time of the production unit.

Importance of Cooperation

The successively higher complexity of the technical systems, we deal with nowadays, makes a more integrated cooperation necessary between different people involved in the origin, installation and commissioning, operation and maintenance of these systems.

Earlier I touched upon the collection of operation experience data for systems, sub-systems and components, to be used in projecting and design work for new equipment. The importance of systematic collection and analyses of knowledge should be obvious. This fact is recognized in big organizations, who can afford to let skilled designers use this information when developing the organization's own equipment. Big suppliers of capital goods with a limited number of buyers can cooperate with these to acquire their experience. This is however a much more difficult task, when smaller companies cannot afford to make the work or when a supplier has a large number of customers, and the necessary correspondence with all these would be too big and complicated and consequently expensive work.

The importance of acquiring service experience data from all sources makes it however worthwhile for all buyers of technical systems to cooperate in this way. How to do this efficiently has yet to be found in the sense of generally applicable methods. It is no doubt one of the factors of great importance in the development in this field.

Experience data available or not available however, a close relationship between the supplier and the buyer, before the contracts are concluded and the specifications decided on, will do much to avoid unpleasent surprises for the responsible operator after the commissioning. The supplier should be asked to specify and to prove the availability of the system to be, before the contract is concluded, and the two parts should agree, what environment and operation conditions the design should be based on. There is still a lot of hesitation among even famous suppliers to the world market about specifying and proving security of function and maintainability and the necessary maintenance security for attaining a reasonably satisfactory and reasonably certain tool systems reliability performance.

This can be done to afar greater extent than is usual. Of course it is done, but all buyers of complex technical systems should be more conscious about the money which is hidden in this concept and should press harder when dealing with their suppliers about future contracts.

With this statement I arrive at my other point of necessary cooperation. Notwithstanding systematically collected experience, experience of course is available in form of the technical knowledge of the experienced technical operator specialists at the buyer's. This experience should be brought to bear on the new design. It is not very much new in this. This is usually done during the negotiations when a specification is considered. It happens as well, but not as much as it should, to my opinion based on experience, that the future maintainers are called up to take part in these negotiations and to put their wishes, based on their experience, to bear on the new equipment in time. In time means before the contract is concluded. Not after. When the contract is concluded the influence on the design from the aintenance point of view, and in fact from any point of view, is very small. The oney involved is to be earned - and this is a very important point - mainly before he contract is concluded.

Of course it is possible to carry through many wise discussions during design nd specially during installation and commissioning. Many small but important bservations about maintainability, inspection routines and other well known aintenance points, can contribute to the future economy. No doubt about that. he most important contributions however is made at the project stage. And here is here the systems engineering comes in. Systems engineering is, according to a efinition given lately by an important British industrialist, "to handle available nowledge and put it to proper use, where it is needed". To cooperate with technical pecialists and maintenance specialists and systemise their knowledge, where it might acquired, to bring it to proper use in the appropriate situation, to be used as base r the successive decisions in the project process, that is the Systems Engineers job. Such people are not seldom available at the supplier's, at the buyer's or as consultants. The last alternative is of great advantage, if these consultants do not have any economical ties with such supplier's, which can be considered in the actual case, and therefore have no obligations except to the buyer they work for.

In complicated cases with large and expensive projects it is mostly of great advantage to have a project leader, preferably an experienced person at the buyers, who is to take charge of the installation in the future operative phase, as production superintendent. He wants to see to it, that his future job does not get upset by surprises. He will do what ever is possible to handle available knowledge and put it to proper use. He will see to it that he gets a project group representing operators, technical specialists, working for a good capability, maintainers working for a high reliability and systems engineers who can help him to control, that all knowledge is put to proper use, that all important questions are asked and answered in time for the development of the project process and that everything possible is done to specify availability measures as well as availability verificati in the contract.

A suitable Project Organization is shown in principal in the following table:

	Contributed from
MANAGEMENT	
PROJECT LEADER	Buyer's Staff
Systems Engineer Project Process Capability - Specified - Proven Availability - Specified - Proven Life Cycle Cost	Consultant if not from Buyer's staff
Technical Specialist Operators Capability - requirements - verification	Buyer's Production Dept. Buyer's Development Dept. Supplier's Design Dept.
Maintenance Specialist Maintainers Availability - requirements - verification	Buyer's Maint. Dept. Buyer's Development Dept. Supplier's Design Dept.

Different Types of Systems

The discussion up till now might seem to indicate that from a reliability/availability point of view all systems are more or less similar. Of course they are not. Principally the request for life cycle cost consideration is the same but the way to do the work and specially the weight on different stages of the work differs.

Very roughly we can speak of systems, produced in long series contrary to unique systems and of complex systems contrary to uncomplex systems.

Systems in long series are sold to a large number of buyers, e.g. cars, refrigerators and passenger aeroplanes. For those it is not possible to have co-operation during the project stage for acquiring, systemizing and utilizing all collected experience. The supplier has to act much more on his own, has to utilize laboratory tests and prototype work and has to offer his customers a more or less standardized product. Often the supplier seeks out a panel of users for testing out his equipment. The more expensive type of equipment and the more expensive any failure on the prospective market, the more money must be and can be spent on such preparations as laboratory, prototype and panel-testing work. If on the other hand we have to do with a fairly short series or just one unique system for one client, then the whole programme with the project group manned with representati for both parts is the correct thing to do. If we assume that much money is involved such as for military equipment or commercial ships or a factory with a number of machinery units, the whole system engineering project programme will undoubtedly pay off for itself. The risk for unpleasent surprises is bigger in the same proportion as the money involved is bigger. The more money involved, probably the more people, prospective customers, government and community officials. The more money spent on the system itself, probably the more money spent on environmenta investments, streets, housing, transport, other community service, etc. Consequentl the more mutual obligations and therefore the more carefullness is justified in the project planning.

The other comparison, complex and uncomplex systems, is perhaps rather more obvious from this life cycle cost/reliability point of view. The more complex the system, in the sense of more inter connected components, more components dependin on each other in a more complex structure to fulfil the systems function, the bigger risk for deterioration of the function due to failure in one sub-system or the other. Consequently the more complex system the greater weight on a good planning, whether this falls to the supplier alone or to the buyer as well in some sort of cooperatio organization. More uncomplex systems naturally cannot cause very much of surprise the competence necessary for designing suitable systems for the intended function is to a greater extent of a pure technical character. The good technician solves the problem without bothering himself too much about project process/reliability - availability/life cycle cost problems. Then it is probably more a matter of finding out what the market requires and see to it that these requirements are fulfilled.

Summing up

Under this rather ambitious headline, quoted from the title of a novel by the famous author Somerset Maugham, I would like to draw some conclusions of the discussion around the characteristic of availability. I have tried to build up the conception that the reliability performance expressed f.i. as availability is a property of any system, which is consistent with the capability property. The availability should be specified when a buyer/supplier negotiation about a proposed system is going on. It should be not only specified as definitely and exactly as any other technical property f.i. stating the capability, it should also, in the same way as these technical properties, be subject to exact agreements about how to measure the specified properties when delivery tests are carried out.

This is a difficult task, no doubt about that, but the more energy is spent on this task the more benefit is achieved in a better knowledge of what can be expected of the new system's productivity, or cost/effectiveness relation. The difficulties are probably in many cases overwhelming, if the objective is to state the system's total availability and cost/effectiveness. If the available experience from similar, earlier system is not complete enough, the contract cannot be very specific about these properties. It would however be possible f.i. to state, that by specified tests the maintainability should be proved and that by specified tests of the critical component's security of function, combined with reliability calculations according to agreed methods, the system's total security of function should be proved. Farther it would be quite possible to let the specification cover a detail description of the documentation necessary for a planned preventive inspection routine, for a maintenance information system, and for the organization of the necessary maintenance teams and for supplying these with appropriate tools, spare exchange units and spare parts, handbooks, space and transport facilities.

The spare exchange unit and spare part question is a very important one. The base for a good solution comes from a good system engineering work in connection with the project anddesign process of the system. The part questions in this field are such as these: How many and which units and spare parts in stock at the buyers? How many at the suppliers? Can any of them be ordered for production when they are required for repair work and thus not carried in stock? If the parts are usable for several systems located far apart, where should the parts in stock be located, close to the systems in question or in some central stock? Specially the dimensioning of the spare part stock is economically very important. To have too many parts in stock is very expensive. Too few parts in stock can suddenly lead to a very unpleasent down state, waiting for a missing part, when production demand is severe. To find the right balance is a bit of systems engineering.

It might be a fruitful idea to consider the possibility that UNIDO includes in its support activities for industry in the developing areas, a service of systems engineering work, directed towards the reliability performance of the equipment, delivered to the industry in these areas.

The important thing is, that the buyer gets support to evaluate for his special purposes and his special environment conditions, the different proposals put forward. If this evaluation is made by organizations, authorized by UNIDO, this would be a guarantee for the buyer, that he has a good chance to receive the best equipment for his purpose.

So my suggestion to which I would like to concentrate my "summing up" is that we all ask UNIDO to earnestly consider how a Reliability Engineering Centre could be attached to its organization, which could furnish service when this is requested by buyers of complex equipment.

Such service is not very easily given. The buyer of this service must have enough knowledge of maintenance reliability and system engineering to be a competent buyer. He must be able to cooperate with system engineers and reliabilit and maintenance experts in a constructive manner. By these conferences and by the training given in various maintenance courses this condition is created.

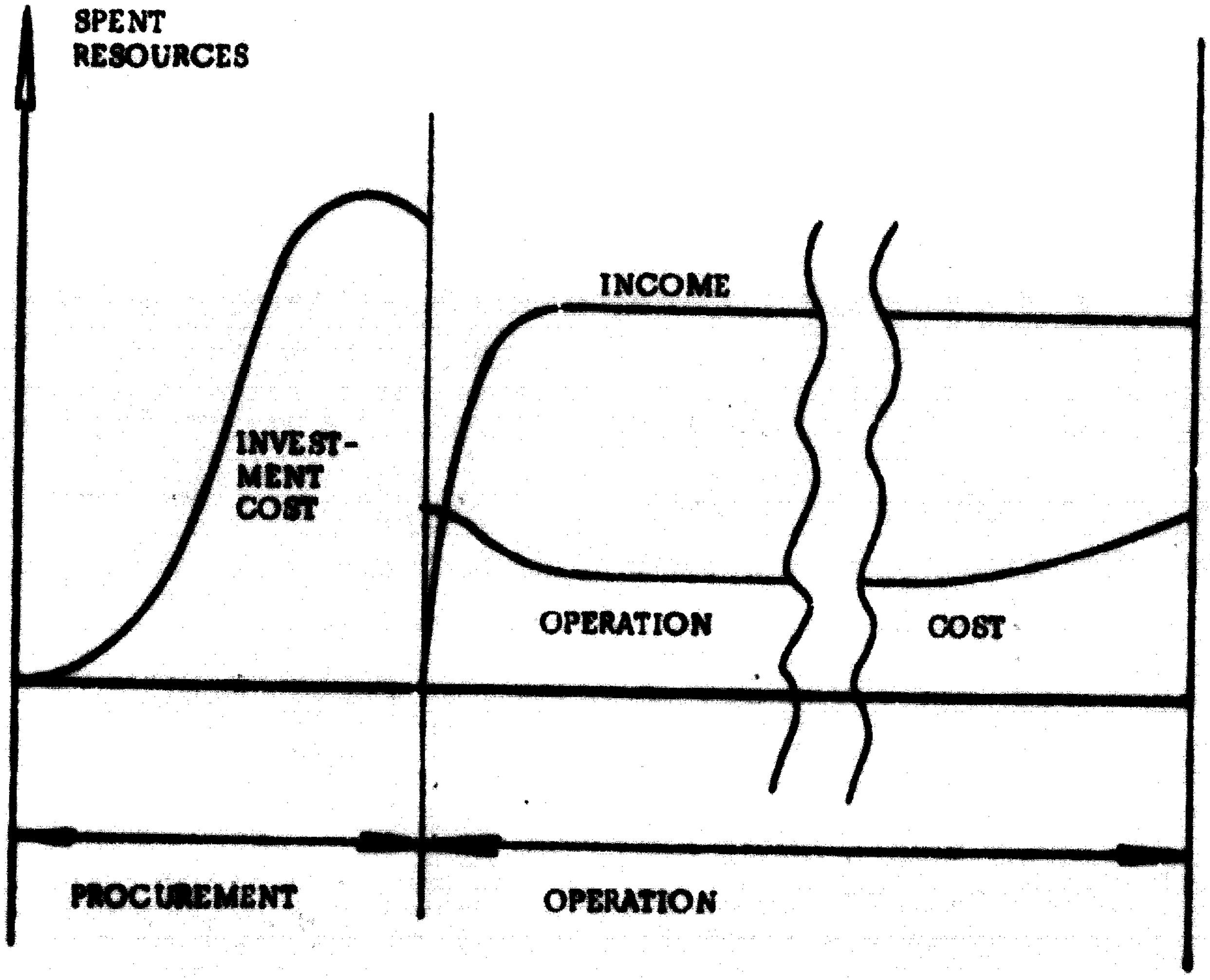


FIGURE 1

COST AND INCOME DISTRIBUTED OVER LIFE TIME

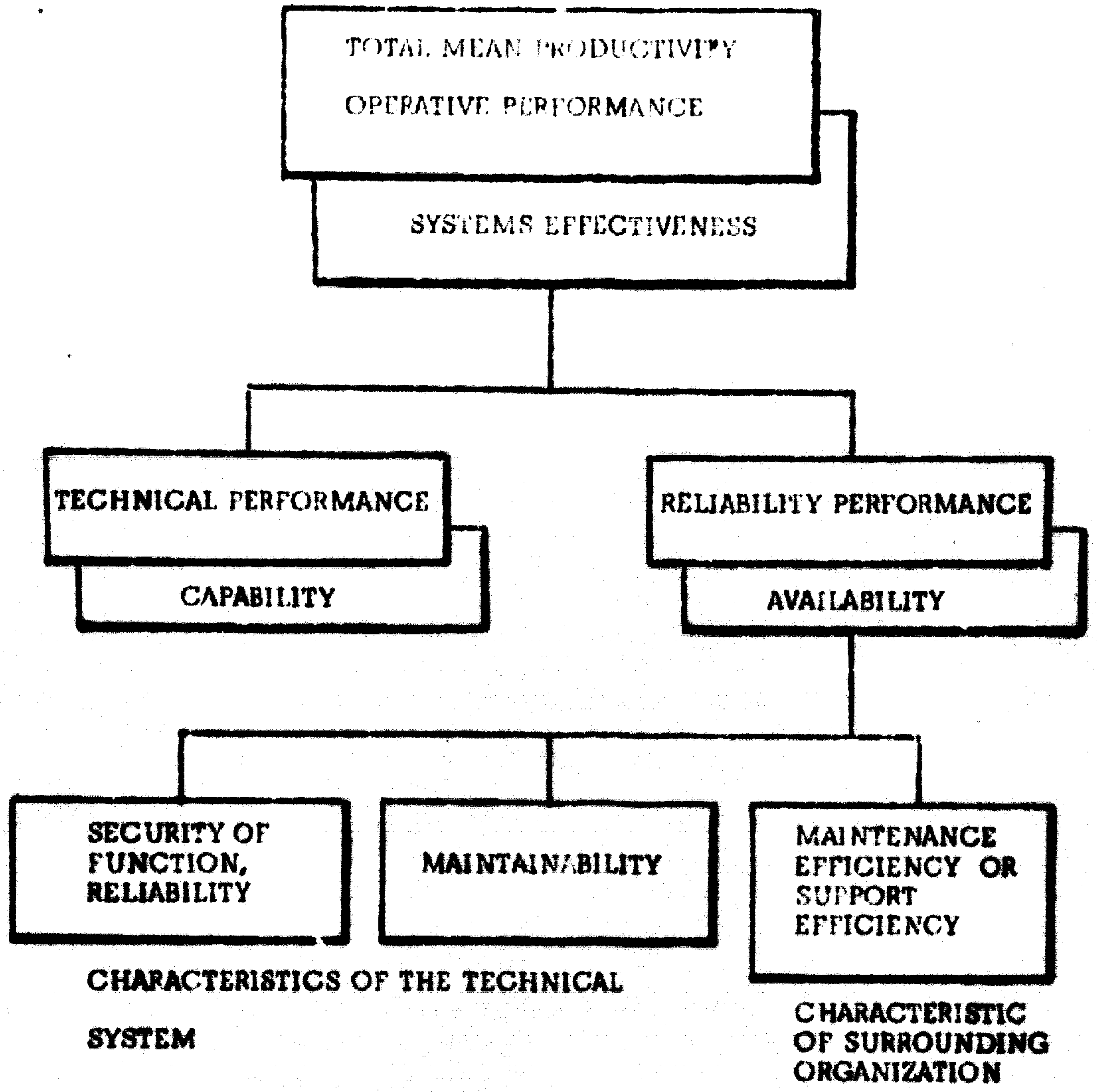


FIGURE 2

SYSTEM MODEL

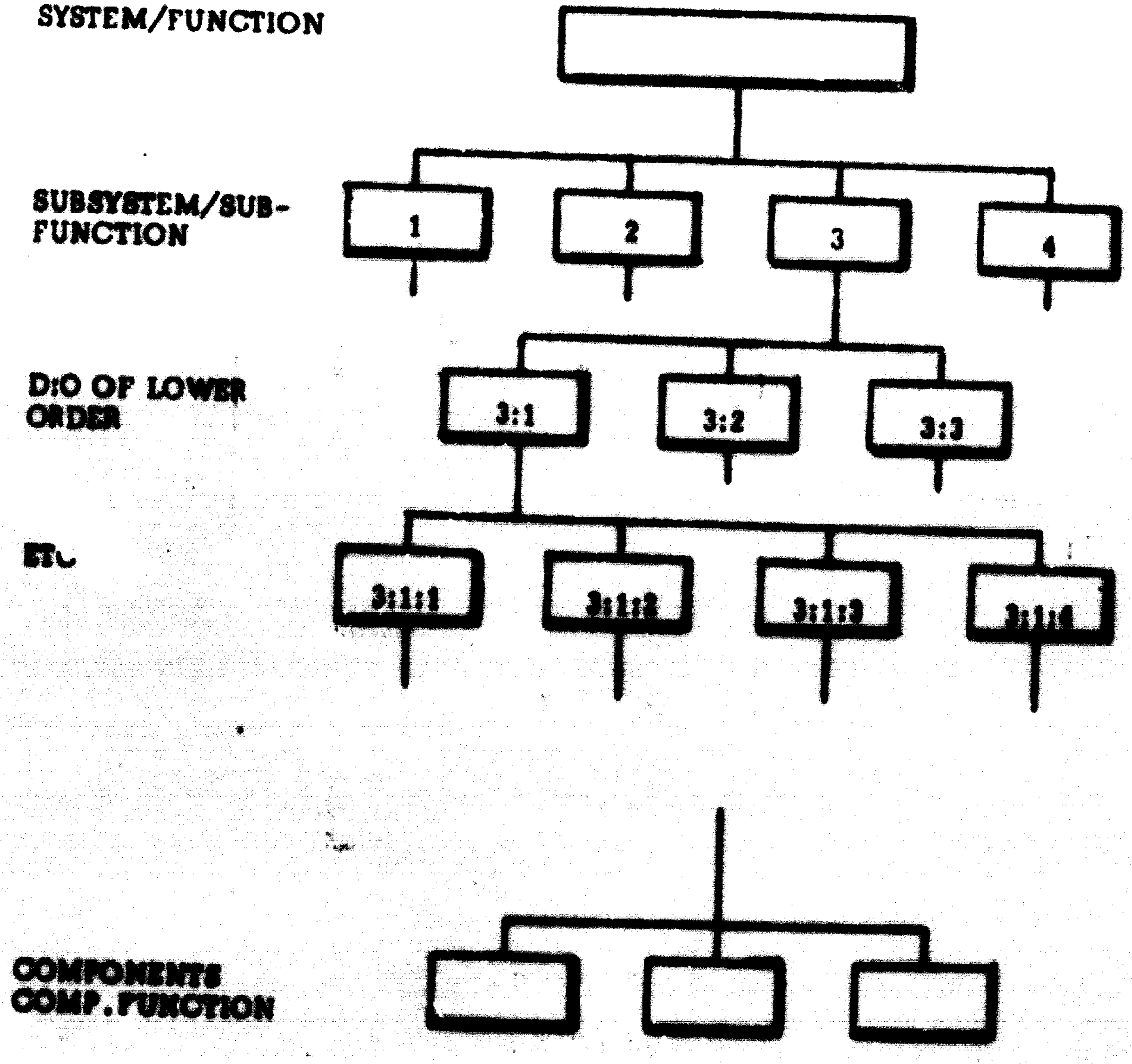


FIGURE 3

FUNCTIONAL SYSTEM BREAK DOWN

FOR IDENTIFYING THE SYSTEM STRUCTURE

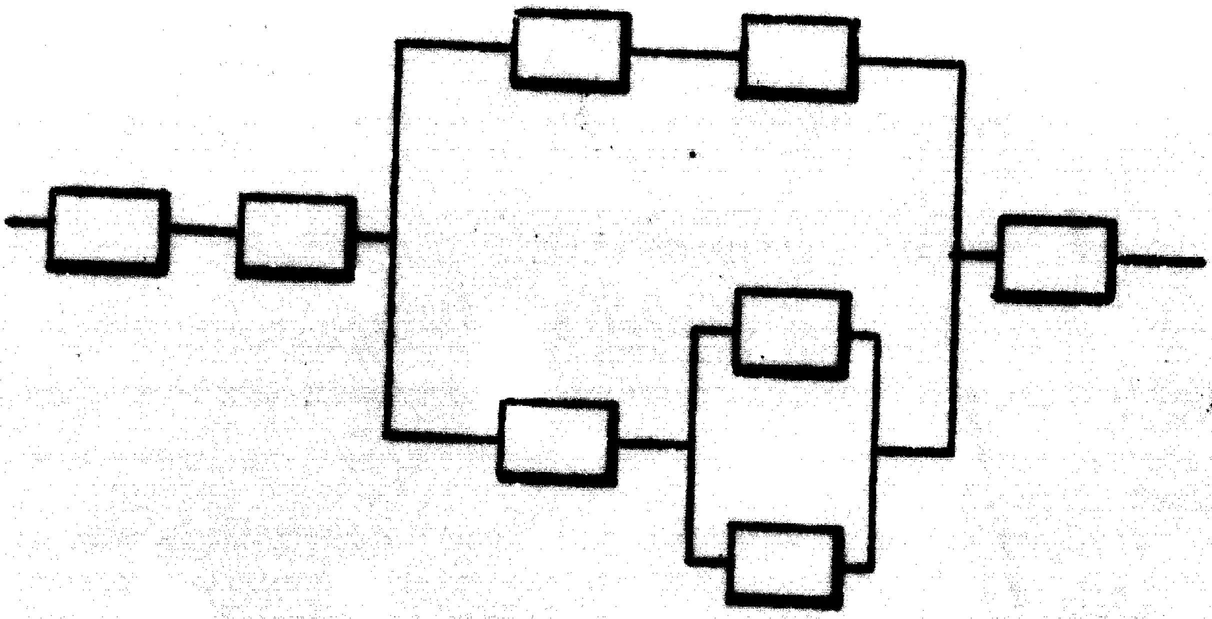
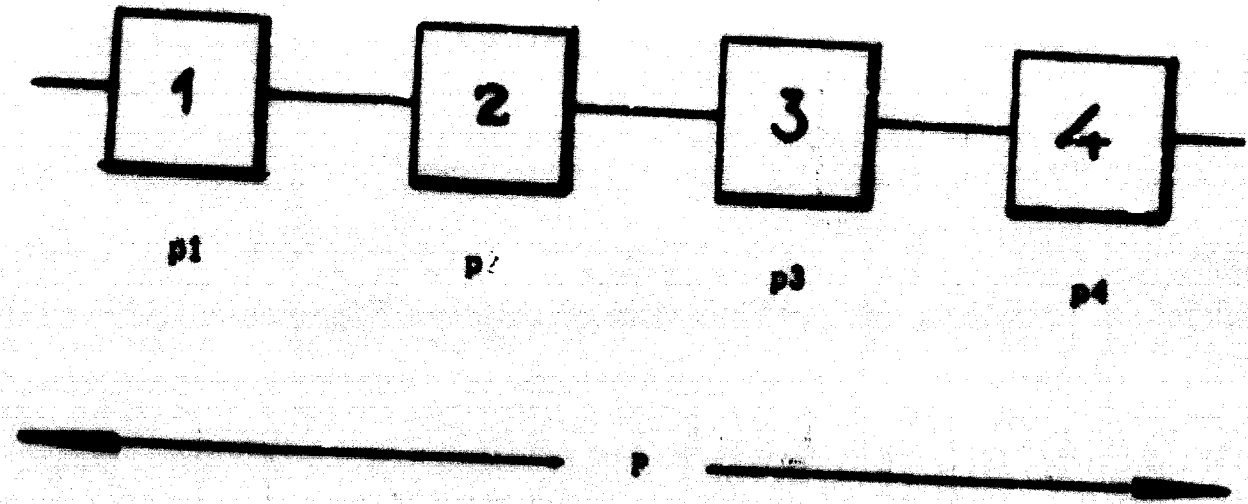


FIGURE 4

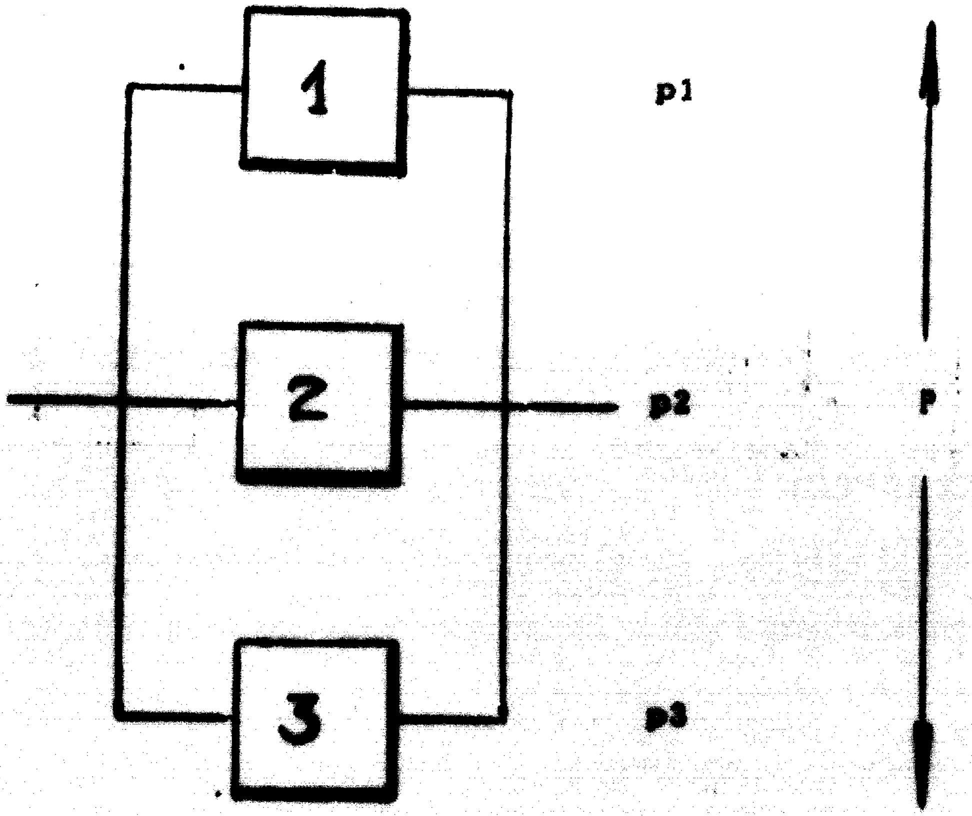
RELIABILITY DIAGRAM



$P = p1 \times p2 \times p3 \times p4$

FIGURE 5

SECURITY OF FUNCTION, SERIES



$$(1 - P) = (1 - p1)(1 - p2)(1 - p3)$$

FIGURE 6

SECURITY OF FUNCTION, PARALLEL

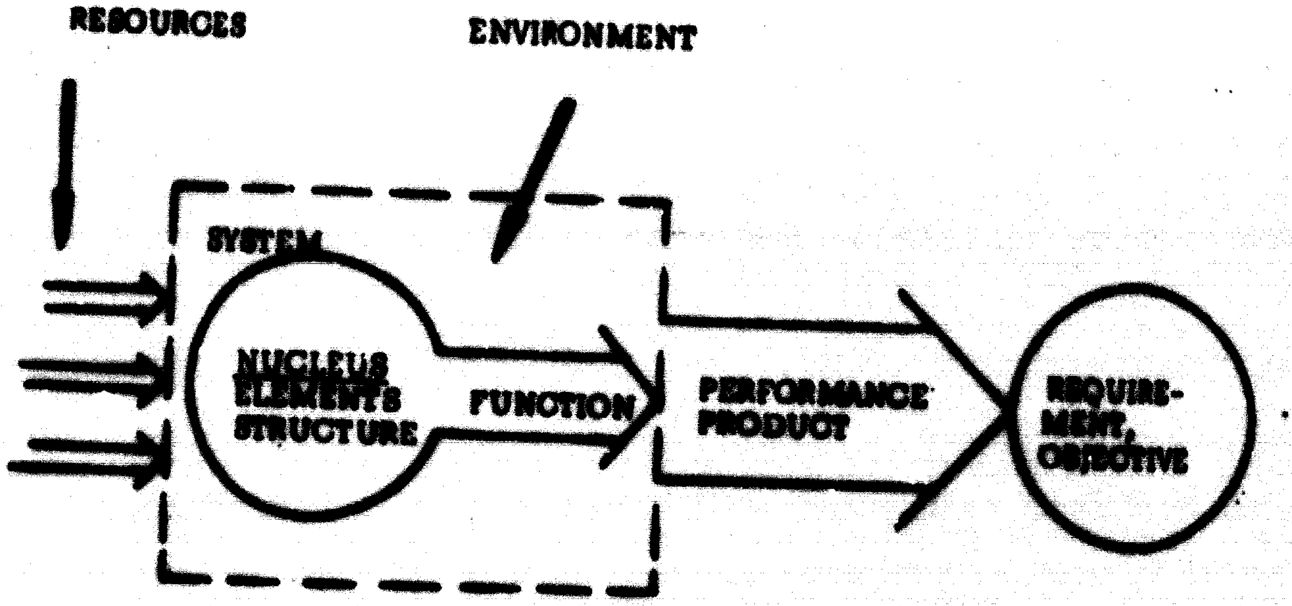


FIGURE 7

SYSTEM MODEL

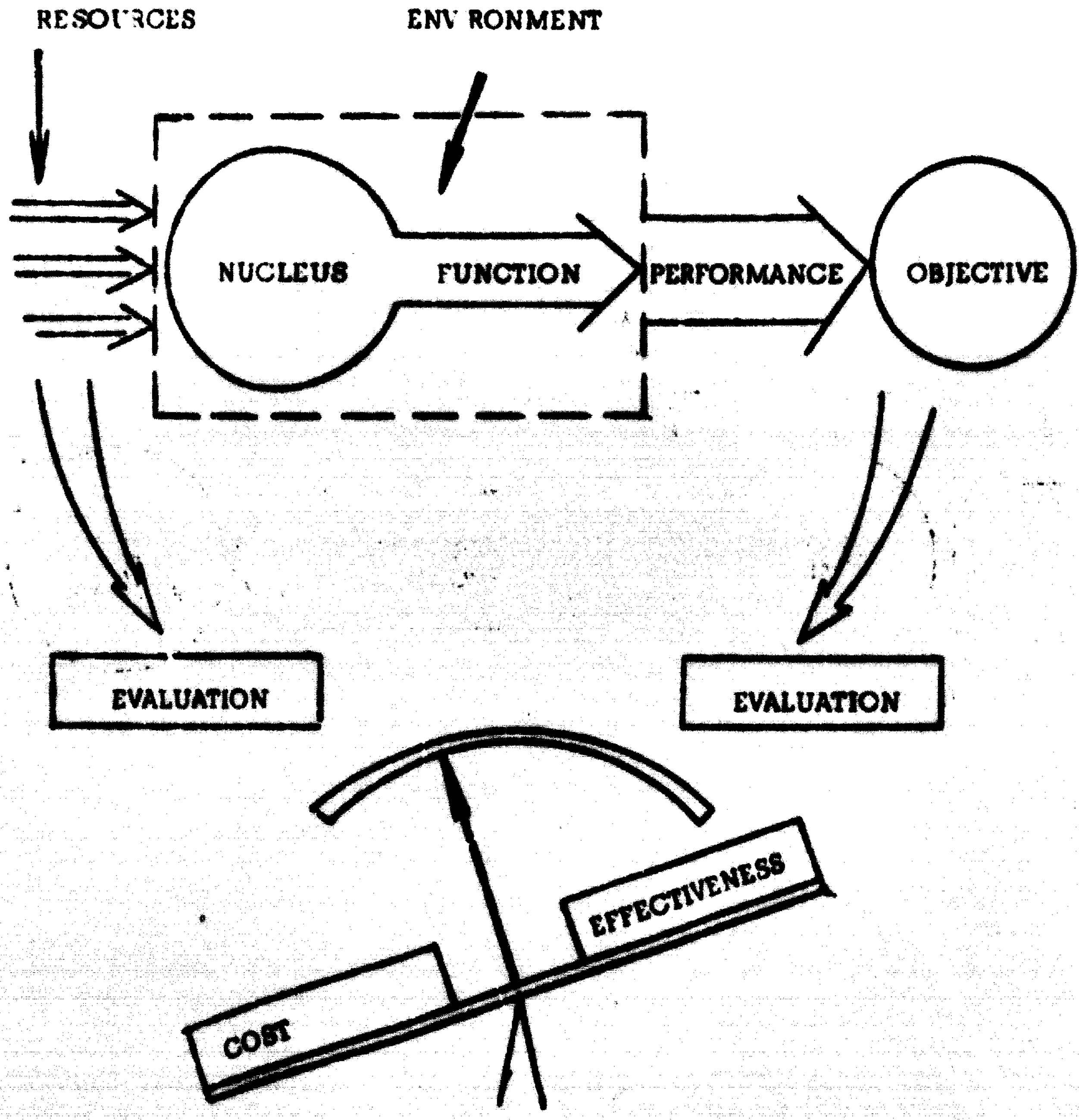


FIGURE 8

COST - EFFECTIVENESS MODEL

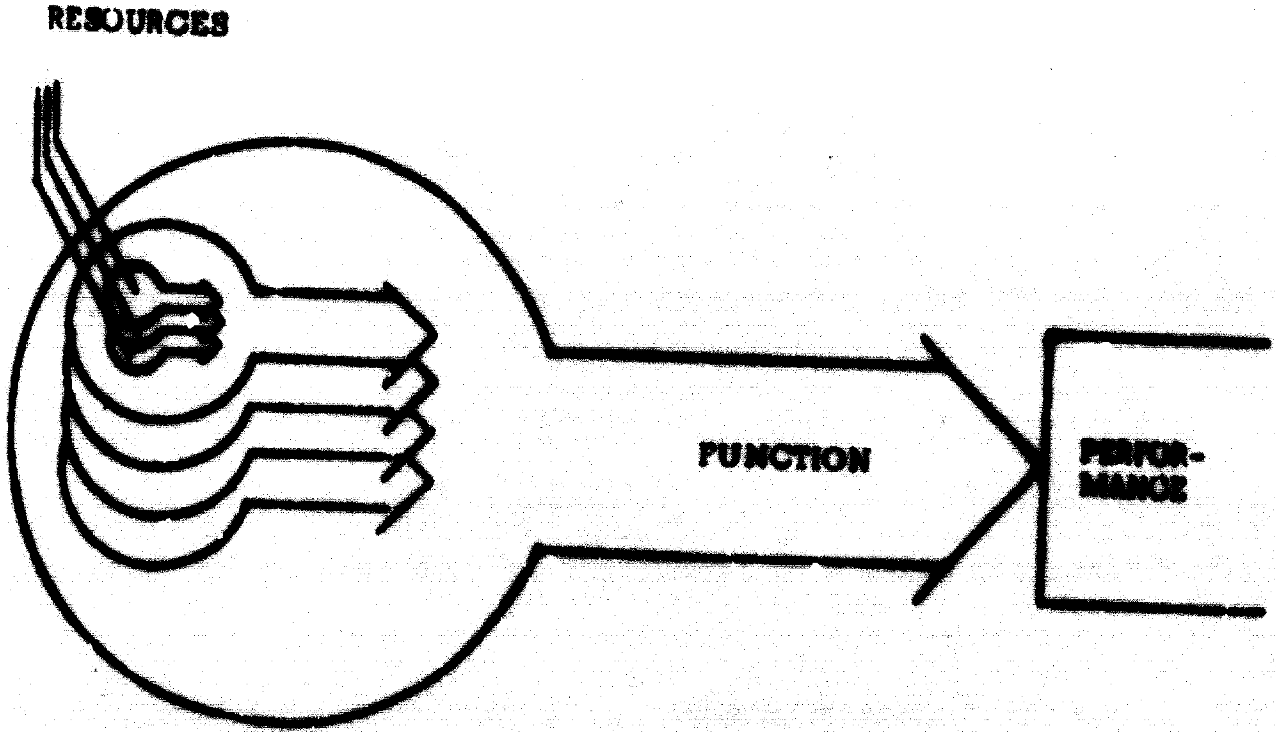


FIGURE 8

SYSTEM MODEL

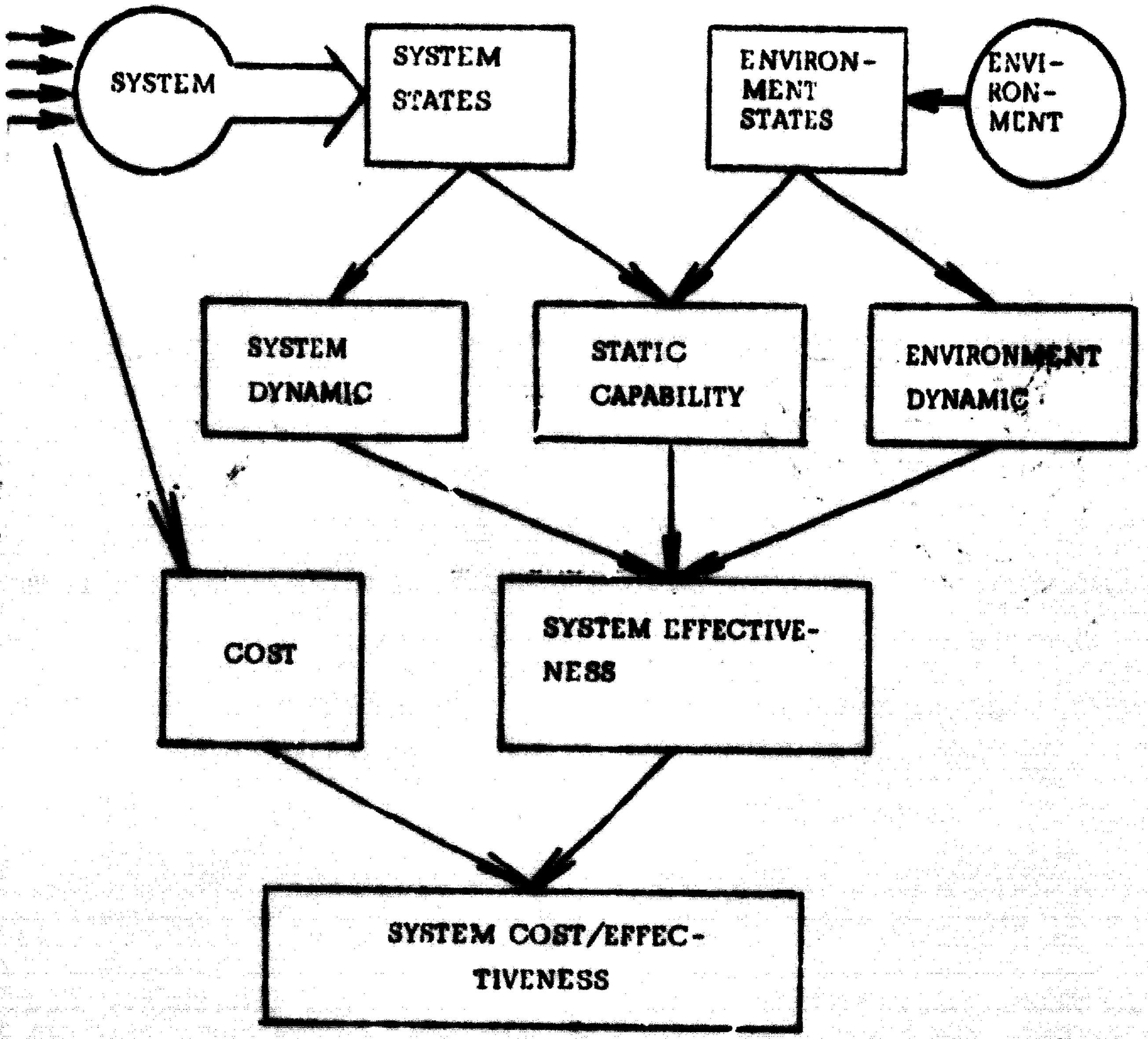


FIGURE 10

COST - EFFECTIVENESS MODEL WITH SYSTEM AND ENVIRONMENT DYNAMICS

Example of application of the Ebenfelt - Holmqvist "Dynamic System Concept"

This example shows a fire control station for an artillery or missile battery. Such a system can have a number of function modes with different combination of its radar-, laser- and infrared instruments for measuring range and direction to a target during the time this target is approaching. The function modes are shown in this table:

Function mode	Range information	Direction information
A	radar	radar
B	laser	I R
C	radar	I R
D	laser	radar
E	laser	laser

The system also is constituted by a central unit, producing electric power, calculating the information into direction and fire orders to the guns (missile launchers) and controlling the function of the different parts of the system.

The sub-systems are assumed to have known, predicted patterns of failure rate. The mean time to repair occurred defects is predicted to be known and for the sake of simplicity constant for all defects. All is valid during a certain actual time period, at which the study is aimed. The environment, surrounding, in this case is defined as a number of tactical situations, characterised by different combinations of the conditions: reduced visibility by fog or clouds, electronic countermeasures (ECM), optical countermeasures (OCM) which all reduce the capacity or the tactical value of the system. Following table shows these combinations.

Tactical situations	Environment factors		
	Reduced visibility	E C M	O C M
S 1	-	-	-
S 2	+	-	-
S 3	-	+	-
S 4	-	-	+
S 5	+	+	-
S 6	+	-	+
S 7	-	+	+
S 8	+	+	+

The probability for any of the environment factors to prevail during the assumed or considered enemy contact situation is estimated by tactical experts and the probability for the different tactical situations S 1 - S 8 to prevail is a consequence of these judgements. The series of probability figures, which are arrived at in this example are

0.24 0.16 0.18 0.12 0.12 0.08 0.04 0.04

and is an expression for the environment dynamics, the "environment vector".

The tactical capability of the system, which is a consequence of each pair of function mode and environment state, can be established by known methods and can be represented in a matrix. In this example this matrix is given in the following table where the figure 1.00 represents the maximum capability with no defects and the ideal tactical situation.

Environment State	Function mode A	B	C	D	E
S 1	1.00	0.95	0.95	1.00	0.90
S 2	1.00	0.03	0.60	0.05	0.02
S 3	0.25	0.95	0.48	0.50	0.90
S 4	0.25	0.03	0.30	0.02	0.02
S 5	1.00	0.08	0.08	0.10	0.01
S 6	1.00	0.02	0.50	0.05	0.00
S 7	0.25	0.05	0.40	0.05	0.01
S 8	0.25	0.02	0.25	0.02	0.00

The probability for function, a measure of the operative availability, depending on the predicted failure pattern of the sub-systems now comes into the picture and causes a further deterioration of these capability values. The probability for function has been calculated under certain presumptions:

- Failures are repaired in the order they occur, if this makes the system able to furnish range as well as direction information.
- Otherwise the central unit has priority 1 and the radar priority 2.
- One repair team repairs one defect at a time.
- The operation crew always tries to use that function mode, which gives the best capability in each environment state.

- If more than one failure occurs at a time, so that the whole system is in a down state, it is switched off. All failure rates then are considered equal to zero.

The system now has a number of combinations of function modes and function or failure of the sub-systems. This gives a large number of system states, in this example 22. The probability that the system is in any one of these states can be calculated by known methods and the series of probability figures is an expression for the system dynamics, the "system vector". In this example it is established that the probabilities for the states 9 - 22 are small enough to be uninteresting.

In the states 1 - 8 the probabilities are:

0.9363, 0.0140, 0.0002, 0.0168, 0.0003, 0.0002, 0.0112 and 0.0002.

The state pairs, environment situations S 1 - S 8 and the system states 1 - 8 are expressed in the following matrix giving for each pair the calculated capability.

Environment situation	System states 1	2	3	4	5	6	7	8
S 1	1.00	0.95	0.90	1.00	0.90	1.00	1.00	1.00
S 2	1.00	0.03	0.02	1.00	0.02	1.00	1.00	1.00
S 3	0.95	0.95	0.90	0.90	0.90	0.25	0.48	0.25
S 4	0.30	0.03	0.02	0.25	0.02	0.25	0.30	0.25
S 5	1.00	0.08	0.01	1.00	0.01	1.00	1.00	1.00
S 6	1.00	0.02	0.00	1.00	0.00	1.00	1.00	1.00
S 7	0.40	0.05	0.01	0.25	0.01	0.25	0.40	0.25
S 8	0.25	0.02	0.00	0.25	0.00	0.25	0.25	0.25

Now it is possible to calculate, by known trivial mathematical methods, out of these capability figures and the series of probabilities for each state of environment and system, the mean capability to 0.8159, i.e. 82 % of the maximum possible value if the system is working without defects and the tactical situation is ideal

It is also possible to calculate that in the least favourable situation the state S 8 the mean capability is 24 % of the highest possible. The state S 8 is when with reduced visibility, the enemy is using both kinds of countermeasures.

This example is rather trivial but illustrates how it is possible to approach a problem where two dynamic conditions independent of each other influence the resulting solution.

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