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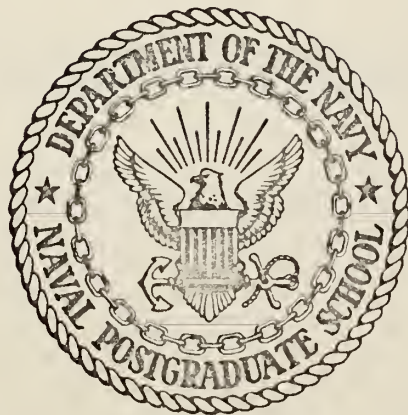
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COURSE SCHEDULING TO FIND THE
MINIMUM COST SET OF FACILITIES REQUIRED

Luis A. Seccatore

NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

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by

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Thesis Advisor:

G.T. Howard

September 1972

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Course Scheduling to Find the
Minimum Cost Set of Facilities Required

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The problem of determining the quantity of classrooms, laboratories and instructors to train sections of students attending numerous distinct courses in a school such as the Fleet Ballistic Missile School is considered.

A procedure is developed for determining feasible schedules in order to graduate a fixed number of trainees over time while minimizing the cost of facilities mix required.

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I. INTRODUCTION

The problem of determining the capacity of a school to train sections of students attending numerous distinct courses has been considered by Willingham [1] as an optimization problem. He used linear programming techniques for determining the maximum number of convenings of each type of course taught at the school which can take place during a year period subject to resource constraints and lower bounds on the number of convenings of each type of course.

This problem arises with the conversion of FBM submarines from Polaris to Poseidon missile systems. There exists the necessity of assuring a proper quantity and mix of resources to instruct all required personnel at the Naval Guided Missile School. Here the primary resources of interest are laboratory facilities of various types with their associated equipment, classrooms and instructors of each specialty pertinent to Poseidon technical training [1].

The problem as stated from the point of view of those responsible for the funding and operation of the school is: "Given the planning estimates from BUPERS of the number of personnel who require training in each type of course over a specified time period, determine what level and mix of resources is adequate to carry out the mission." The present work will consider this last aspect of the problem,

attacking it under the assumption that carefully scheduling the convenings of each section will yield to a minimum requirement of resources for a given time period.

The above idea can be expressed more precisely and in general as follows: An important function of any school planning is to estimate the number of facilities, namely laboratories, classrooms and instructors, that are needed to support a specified program of instruction and to specify, in general terms, the schedule to obtain the best employment of the resources. By a specified program we mean the type of courses to be taught, their curricular requirements and the quantity of students assigned to each one. The problem is, then, to find that schedule which requires the least cost set of facilities.

Since a particular schedule dictates a required set of facilities, it is necessary to have a measure of some characteristic in order to be able to compare it to other feasible schedules. A measure of effectiveness of a schedule will be defined as the cost involved in the installation of all facilities associated with it.

In general, specifying a measure of effectiveness in a scheduling problem is specifying a set of equivalence classes of schedules and a preference ordering among these classes. For example, specifying the cost of the facilities needed as the measure of effectiveness for a particular problem means that:

- (a) All schedules that have a cost C_0 are equivalent, so

one is indifferent as to which schedule is selected.

(b) A schedule with cost C_1 is preferred to a schedule with cost C_2 if and only if C_1 is strictly less than C_2 .

From the above discussion it can be seen then, that the minimal cost scheduling problem is one of evaluating schedules and the associated combination of resources in the search for the minimum cost. It is clear that there is a very large number of possible schedules for the problem. It is also clear that most such schedules are uninteresting for reasonable measures of performance and only a few are worth considering.

Although the least cost facility mix scheduling problem is easy to state and to visualize, no easy solution is available. Evaluating the set of all feasible solutions (represented by all possible combinations of schedules and facilities) is, for practical purposes, a gigantic quest. The objective of this paper is to illustrate a method of solving the problem applying the concepts developed in [2]. A procedure will be presented for approaching one schedule of the equivalence class of schedules that requires the least cost of the resources for a given program of instruction for a given time period.

A first attempt to obtain an acceptable solution to the scheduling problem can be made by evaluating the costs of random schedules which, consequently are random variables too, estimating the distribution of the costs, and then attempting to estimate the probability that, in a sample of

size n , at least one will be in the lowest fraction P_ℓ of the population. For a discrete random variable, as will be the case here, let p_r be the probability that a single observation has a cost value equal to r . Then the probability that the smallest member of a sample of size n has a cost value less than r is given by:

$$P[Z_{\min} < r] = 1 - (1 - P_\ell)^n \approx 1 - e^{-nP_\ell}$$

$$\text{where } P_\ell = \sum_{i=1}^{r-1} p_i, \quad Z_i < r.$$

For obvious reasons it is desirable to have an estimate of the lowest cost which is as close as possible to the true minimum cost of all possible schedules. Thus P_ℓ must represent a very small fraction of the lower tail of the distribution. Consequently the individual p_i 's, near the extreme are very small thus the probability is small that the most extreme cases will be presented in any random sample of feasible size [4].

If a sufficient amount is known about the population distribution such that it is possible to calculate approximately the probability that an observation is less than a specified value, not far from the extreme of the distribution, then the number of further observations necessary to improve on this value could be estimated. However, before an improvement is obtained, a large number of useless values may be found. These considerations imply that the

rate at which useful information obtained by random sampling is much less when estimating extremes than when estimating means.

As in any combinatorial problem the task of evaluating the distribution of the cost due to schedules is far from being easy and is time consuming. The suggestion is, therefore, to employ some kind of heuristic algorithm on the search for the least cost value. If a schedule is generated at random and reductions in the cost involved are obtained by applications of the heuristic mechanism and the process is repeated n times, then the n lowest costs generated will tend to be a random sample of extreme values from the n samples originally generated from the parent distribution. Then a Weibull distribution can be fitted to the data. The Weibull has the characteristic of being independent of the parent distribution and has as one of its own parameters the minimum value in question, [2], [3].

The approach to solve the problem presented in this study is first to develop a mathematical model to determine the relationships between schedules and facilities mix having the cost of the resources needed as the schedule's effectiveness measure. Thereafter, to generate a random starting date for each section of each course and to determine the cost of this schedule as given by the model; then by means of an heuristic procedure applied on that schedule trying to reduce the cost involved such that a local minimum cost schedule is found. Finally to use a sample

of such schedules to estimate the parameters of the Weibull distribution so that a decision can be made: whether to stop or to generate additional random schedules and to repeat the estimation of the parameters.

This thesis is organized in four sections. In Section II is developed a mathematical description of the behavior of a school which must train personnel. In such a school the courses taught can be of different lengths and each one can be composed of one or more sections, depending upon the necessity of skilled personnel. It will not deal directly with the problem of a time-table of meetings within each week. It is assumed that each type of facility is available a fixed number of hours per week and the number of trainees required in a year for a given course (or specialty) is divided into sections and they are scheduled to start at sometime during the year. It is this scheduling problem with which this thesis deals.

Section III deals with elements of the theory of extreme values and the Weibull distribution. This distribution has the feature of being bounded and describes the behavior of the extreme values taken from samples independently drawn from any parent population.

In Section IV is proposed a heuristic cost reducing procedure and a stopping decision rule. Even though the procedure is rather slow in finding a local minima and was not used in the examples discussed in Section V, it is presented here because, in the author's opinion, it has

the essential characteristics required by an algorithm to be useful for this problem.

In Section V the results of an example involving a hypothetical school are presented and the findings discussed.

In Appendix A is presented the schedule similar to that proposed in [1] that has the feature of being balanced, in the sense of facility usage by the sections of a given course throughout the complete period.

The computer program for the scheduling algorithm and a brief description of it are included in Appendix B. The program was run on the IBM 360/67 system in the "W. R. Church" Computer Center at the Naval Postgraduate School, Monterey, California.

II. THE MODEL

The major assumptions in the model are:

- a. Course curricular requirements are given in the course syllabus.
- b. Each unit of a specified facility is available a fixed number of hours per week.
- c. The total number of students requiring instruction is nearly constant and small changes can be absorbed by varying the size of the sections.
- d. A section is a physical group of students receiving a specified type of instruction.
- e. No restriction is placed in the order in which the courses are taught, i.e., no course has preference to any other course. Any section of any course is equally likely to start at any time of the period.

A. FORMULATION OF THE MODEL AND NOTATION

Let $I = \{i: 1, 2, \dots, L\}$ be the set of all different types of courses that are taught. Let N_i be defined as the number of sections of course i which must be taught during the period of one year. Let $S_i = \{s: 1, 2, \dots, N_i\}$ be the set of sections of course i , for all $i \in I$.

Define $J = \{j: 1, 2, \dots, M\}$ as the set of all types of facilities such as classrooms, laboratories and group of instructors. In the model $j = 1$, is reserved to designate the classrooms.

Let $K = \{k: 1, 2, \dots, T\}$ be the set of all working weeks in a specified period of time which is one year and let M_{jk} be defined as the number of units of facility j required in week k .

Let d_i be the duration in weeks of course i and A_{ij} be the total amount of facility required to teach course type i for all $i \in I$ and $j \in J, j \neq 1$. For example, A_{ij} is the number of lab-hours of some laboratory or number of lectures or contact-hours required by the j^{th} group of instructors. We assume that d_i and A_{ij} are predetermined and are given as exogenous parameters to the model by the syllabus of each course.

Sequencing requirements for individual topics or usage of laboratories within a determined type of course is not considered, and it is assumed that the total requirements for facility j by course i is evenly used among the weeks that comprise the duration of the course. Then it is possible to define:

$$r_{ij} = \frac{A_{ij}}{d_i}$$

as the weekly demand of facility j by one section of course i for all $i \in I$ and all $j \in J, j \neq 1$.

Let DA_j be the weekly availability of one unit of facility j , in hours, for all $j \in J$. DA_j is fixed for all $k \in K$.

We would like to set up a schedule such that all sections of all courses are taught during the time period of interest and the costs involved are minimized. Since under the same conditions, the schedules should be the same from one year to another, if a section has not finished its instruction at the end of the 50th week it will be included at the beginning of the cycle for the time necessary to end its instruction.

Define k_{is} as the starting date of the s^{th} section of course i , for all $i \in I$ and all $s \in N_i$, and $1 \leq k_{is} \leq T$. Note that there exist as many schedules as the number of distinct combinations of the k_{is} 's; since, for a given course the sections can always be relabeled the total number of different ways in which they can be scheduled is $\frac{T^{N_i-1}}{N_i!}$. Now for each section of course i there are $\frac{T^{N_{i'}-1}}{N_{i'}!}$ combinations among the sections of course i' , for $i' = 1, 2, 3, \dots, L$, $i' \neq i$. Then the total number of different schedules is

$$\frac{T \exp\left[\sum_{i=1}^L N_i - 1\right]}{\prod_{i=1}^L N_i!} \quad (1)$$

Let δ_{iks} be equal to 1 if section s of course i is in progress during the k^{th} week and 0 otherwise. Then if $k - k_{is} < 0$, the section has not started yet and $\delta_{isk} = 0$; if $0 \leq k - k_{is} < d_i$, the section is in house at week k and

$\delta_{isk} = 1$; if $k - k_{is} \geq d_i$, the section has finished its instruction and $\delta_{isk} = 0$. Note that having δ_{isk} defined in that way implies that $\delta_{isk} = \delta_{isk+1} = \dots = \delta_{isk+d_i} = 1$ when $k_{is} = k$. This insures that once a section has started its instruction it will continue week after week until it is finished.

Summing the δ_{isk} for all $s \in S_i$ in any k produces the number of sections of course i being taught during week k :

$$\sum_{s=1}^{N_i} \delta_{isk} = \Delta_{ik}, \quad \text{for } k = 1, 2, \dots, T \quad (2)$$

Then $r_{ij} \cdot \Delta_{ik}$ represents the amount in hours per week that facility j is required by all sections of course i during week k . Summing over all $i \in I$ will produce the total number of hours of facility j needed to accommodate all courses in week k , $j \neq 1$.

If a given facility is not to be used more than it is available in any week, then we have

$$\sum_{i=1}^L r_{ij} \cdot \Delta_{ik} \leq M_{jk} \cdot DA_j, \quad \text{for all } j \in J \text{ and } k \in K, \quad j \neq 1.$$

Where M_{jk} is the number of units of j which must be provided in week k .

The number of classrooms required depends on the total number of hours of meetings other than in laboratories occurring in a week. Let G be the set of indices j not corresponding to laboratories and $j \neq 1$.

Then $\sum_{j \in G} \sum_{i=1}^L r_{ij} \cdot \Delta_{ik}$ will represent the total number of classrooms-hours needed or the total number of meetings other than in laboratories occurring in week k and must be less than or equal to $M_{lk} \cdot DA_1$, the total availability of classrooms-hours which must be provided in that week.

Then $\sum_{j \in G} \sum_{i=1}^L r_{ij} \cdot \Delta_{ik} \leq M_{lk} \cdot DA_1$, for all $k \in K$.

Henceforth, $M_j = \text{maximum } (M_{jK} : k=1,2,\dots,T)$ represents the number of units of facility j required in the year in order that the proposed schedule, defined by k_{is} , $k = 1,2,\dots,L$, $s = 1,\dots,N_1$, be a feasible one.

B. COST STRUCTURE, AN OBJECTIVE FUNCTION

Since in comparing two different schedules with the same number of sections and courses, the overall operational costs in a year will be essentially the same in both schedules, the objective will be to minimize the initial cost.

Let ξ be the set of starting dates for all sections of all courses, which constitutes a schedule, thus $\xi = \{k_{is}; \text{ all } i \in I \text{ and all } s \in S_i\}$. Given a particular schedule ξ the facility cost can be found from:

$$Z(\xi) = \sum_{j=1}^M M_j \cdot C_j \quad , \quad (3)$$

where C_j is the initial cost of facility j for all $j \in J$. If j is a classroom or laboratory C_j includes elements such as equipment, buildings, offices, etc. In the present study the initial cost to obtain an instructor is assumed to be zero and therefore does not enter in the evaluation of a given schedule. A subjective cost could be attached to the instructors if it was desired to study their influence in the model. M_j must satisfy the following relationships:

$$M_j = \text{maximum } (M_{jk} : k = 1, 2, \dots, T) \text{ for all } j \in I$$

and
$$\sum_{i=1}^L r_{ij} \cdot \Delta_{ik} \leq M_{jk} \cdot DA_j \text{ for all } j \in J \text{ and } k \in K$$

$$\sum_{j \in G} \sum_{i=1}^L r_{ij} \cdot \Delta_{ik} \leq M_{lk} \cdot DA_l$$

$$M_j \geq 1 \text{ and integer,}$$

Δ_{ik} defined by equation (2).

The objective is to find that schedule ξ such that $Z(\xi)$ is a minimum. It is this problem which we treat in this paper. We do not hope to find the minimum cost Z^* exactly but only to estimate its value and find a schedule with $Z(\xi) \approx Z^*$. This estimate will be obtained by using the properties of the extreme-values and the Weibull distribution.

III. EXTREME VALUES AND THE WEIBULL DISTRIBUTION

A. A USEFUL DISTRIBUTION

In this section some properties of the extreme values and the connection to solving the minimum cost scheduling problem will be discussed. Then, using the properties of the Weibull distribution, a procedure will be presented to estimate the minimum cost.

A good presentation of the elements of the theory of extreme values is given by [5], here we only call attention to the fact that the lowest value in a random sample of size n , drawn from a parent population with cumulative distribution function $F(\cdot)$ (given by $Z_{\min} = \text{minimum}(U_1, U_2, \dots, U_n)$ where the U_i are sample values) is treated in [8] under the name Smallest Order Statistic. Weibull in [3] gives the cumulative distribution of Z_{\min} in its most general form

$$F_{Z_{\min}}(z) = 1 - \exp(-\phi(z)) \quad (4)$$

where the function $\phi(z)$ must have the following characteristics [5,2]:

- i) Because in the minimal cost-scheduling problem there exists a true minimum cost such that the minimum value obtained from the sample cannot be below it, this true minimum cost represents a lower bound for the extreme-value distribution. Let ζ be this true minimum value, then

$$F_{Z_{\min}}(z) = 0 \quad \text{if } z \leq \zeta, \zeta > 0$$

$$= 1 - \exp(-\phi(z)) \quad \text{if } z > \zeta.$$

ii) In addition $\phi(z)$ should behave as $B(Z_{\min} - \zeta)$, where B is a parameter that depends upon the extreme-value spread. B must be greater than zero if $F_{\min}(z)$ is a distribution function.

One distribution that satisfies the conditions stated above is the Weibull distribution (in the form given in [2]):

$$F_{Z_{\min}}(z) = 1 - \exp\left(-\left[\frac{z - \zeta}{v - \zeta}\right]^k\right) \quad (5)$$

where

$F(z)$ = The probability that Z_{\min} is less than or equal to a certain value z ,

Z_{\min} = The minimum cost criterion,

ζ = A constant equal to the minimum cost of the population,

v = A constant parameter indicating the value of the variable such that the probability that Z_{\min} is equal to or less than v is approximately 0.63 (referred to as the characteristic smallest value in extreme-value theory),

k = A constant parameter indicating the shape of the distribution. The distribution will be positively skewed, symmetrical or negatively skewed, depending on whether k is less than, equal to, or greater than 3.259.

There is no strong theoretical support in using this distribution but empirical studies have shown the merits of its applicability [2,3]. The function has the advantage of requiring no knowledge of the parent distribution and having as one of its own parameters, the boundary value of interest.

As has been suggested before, the minimum cost obtained after applying a suitable heuristic mechanism to a random value drawn from the parent population can be regarded as an extreme-value obtained from this same population. If the same procedure is repeated n times a sample of n random and independent observations of the extreme-value, i.e. of Z_{\min} will have been obtained. It is then possible to estimate the value of the lowest cost facility mix-schedule by fitting the Weibull distribution to the data.

The author is well aware that the minimum cost samples are discrete and trying to fit it to a continuous distribution will be a source of error. However, for a moderately large sample, the approximation will be close enough so as to accept the estimated lowest cost as a lower bound for any extreme-value obtained. As a general rough guide only, $n \geq 30$ is a reasonable range of values of n for applying approximations in most asymptotic results [8].

B. PARAMETER ESTIMATION OF THE WEIBULL DISTRIBUTION

Let $Z_{\min_1}, Z_{\min_2}, \dots, Z_{\min_n}$ be n independent and identically distributed random variables. Let $Z_{(1)} \leq$

$Z_{(2)} \leq \dots, \leq Z_{(k)} \leq \dots Z_{(n)}$ be the observations ordered according to their increasing size from the sample of minimum costs with cumulative distribution function as (5).

Recall that the distribution of Z_{\min} should be discrete, then what is possible is that several different combinations of starting dates, i.e. schedules, will have the same cost value. Then since observations can be present with differing frequencies, define

$$Z_{(1)}, f^{(1)}; Z_{(2)}, f^{(2)}; \dots \dots \dots Z_{(m)}, f^{(m)}$$

where $Z_{(k)}$ is defined as before, $f^{(k)}$ is the corresponding frequency with which the k^{th} value occurs, and m is the number of different values that Z_{\min} takes. Then, according to [7] an unbiased estimator of the cumulative distribution function of the Weibull distribution is given by:

$$\hat{F}(k) = F_Z(Z_{\min} \leq z_{(k)}) = \frac{\sum_{i=1}^m f^{(i)}}{n+1}$$

and

$$\sum_{i=1}^m f^{(i)} = n$$

Having the data in the proper form and the estimate of the distribution function, the effort is now turned to the task of estimating the parameters of the Weibull distribution. Recall that this particular version of the distribution has three unknown parameters. Although there are more

accurate methods of estimating these parameters [2], we will present a method based on the double logarithm transformation of the distribution function (5) as indicated in [2,3,7]:

$$\log(\log(1-F_Z)^{-1}) = k \log(Z_{\min} - \zeta) - k \log(v - \zeta) \quad (6)$$

This is the equation of a straight line on Weibull probability paper. The slope of the line is the shape parameter k . Although the parameter v is not self-evident from the graph it can be easily estimated as it will be shown later. This procedure or plotting can be repeated for different estimates of ζ , starting with $\hat{\zeta} = Z_{(1)}$ and lowering its value until the best straight line fit to the data is obtained by the least squares method.

The derivation of the regression equations for estimating the Weibull parameters will be done for grouped data. Let $Z_{(k)}$ and $f^{(k)}$ be defined as before for $k = 1, 2, \dots, m$ and the associated cumulative distribution be:

$$\hat{F}^{(k)} = \sum_{i=1}^m \frac{f^{(i)}}{n+1} \quad (7)$$

For simplicity define

$$Y_k = \log(\log(1 - \hat{F}^{(k)})^{-1}) \quad k=1, 2, \dots, m \quad (8)$$

$$\bar{Y} = \frac{1}{m} \sum_{k=1}^m Y_k$$

$$X_k = \log(Z_{(k)} - \zeta) \quad k=1, 2, \dots, m$$

$$\bar{X} = \frac{1}{m} \cdot \sum_{k=1}^m X_k$$

The regression equation as given in [9] is:

$$\hat{Y}_k = \bar{Y} + b(X_k - \bar{X}) \quad (9)$$

where \hat{Y}_k is the estimate Y_k given X_k and b . The slope of the line is given by

$$b = \frac{\sum_{k=1}^m X_k Y_k - \frac{\sum_{k=1}^m X_k \sum_{k=1}^m Y_k}{m}}{\sum_{k=1}^m X_k^2 - \frac{(\sum_{k=1}^m X_k)^2}{m}}$$

Writing the regression line in slightly different form

$$\hat{Y}_k = bX + (\bar{Y} - b\bar{X}),$$

and comparing it with (4) we have b as the value of \hat{k} , the estimator of the shape parameter. In addition, since

$$k \ln(v - \zeta) = \bar{Y} - b\bar{X}$$

\hat{v} , the estimator of the scale parameter is obtained from

$$\hat{v} = \zeta + \exp\left(\frac{\bar{Y}}{\hat{k}} - \bar{X}\right).$$

Once the values of \hat{k} and \hat{v} have been obtained for a given $\hat{\zeta}$, determine the sum of squares of the differences between the values obtained by (8) using (7) and the values estimated by the regression equation, (9), i.e.

$$SQR = \sum_{k=1}^m (Y_k - \hat{Y}_k)^2$$

Repeat this step for different values of $\hat{\zeta}$ such that $\hat{\zeta}'' < \hat{\zeta}'$, until some value of $\hat{\zeta}$, say ζ^* , yields the minimum sum of squared differences about the regression line. The associated estimators of k and v , say k^* and v^* are the estimated parameters of the Weibull distribution and ζ^* is the estimate of the lowest cost, i.e. the estimated value of Z_{\min} .

IV. A HEURISTIC ALGORITHM

Having developed the model and examined the theory of extreme values, the remaining steps are to present a heuristic cost reducing procedure and some kind of stopping decision rule.

A. COST REDUCING PROCEDURE

As stated before, once a random schedule has been obtained, a heuristic procedure designated to find a schedule whose cost is a local minimum can be applied to it. The following heuristic procedure is suggested for moving from a random schedule ξ_1 to another of lower cost, say ξ_1' :

1. For each type of facility there is a maximum number of units required by a given schedule. However, this maximum number of units is not required for every week of the year. Arrange the facilities in order of increasing number of weeks during which the maximum number of units is required. The order in which they will be selected in the searching process is given by the above ordering. In the case of a tie the higher priority should be assigned to that facility whose initial cost is higher.

2. Beginning with the facility that has highest priority, to determine which courses are related to it and order them by decreasing size of the amount of facility required.

3. The search continues by, successively, picking the course which requires the largest amount of the facility, say i , and, with the exception of the s^{th} section, fix the starting dates of all sections of all courses. Change the starting date for section i , i.e., let $k_{i,s} = k$ for all $k = 1, 2, \dots, T$, and compute the cost of the modified schedule. If for some value of k , this yields a cost which is less than the previous one, retain this as a possible starting date for section s .

4. Repeat the steps 1, 2, and 3 until no further improvement is obtained.

The searching procedure possible can be shortened since it is very unlikely that a facility which is fully utilized more than fifty per cent or more can diminished by one unit. Consequently those facilities with usage factor greater than fifty per cent should not be taken into account in the search procedure, neither should those whose maximum number of units is one.

B. A STOPPING RULE

By using the above procedure we obtain a set of schedules ξ_i' whose cost $Z_{\min}(\xi_i')$ can be viewed as a random sample of extreme values. These are, then, used to estimate $\zeta = Z_{\min}(\xi^*)$ the minimum cost value that could be achieved. When translated into a computer program it is necessary to incorporate a rule such that after a number of trials a decision can be made whether to stop or to continue making more observations.

For instance, the following rule could be used if the expected decrease in cost by improving the scheduling is greater than or equal to the cost of one unit of the least expensive laboratory, make additional trials; otherwise stop. Formally

$$\text{if } \int_{\zeta^*}^{\text{ZMM}} (\text{ZMM} - Z_{\min}(\xi)) dF_{Z_{\min}} \geq \text{CI}(\cdot),$$

continue searching. The number of additional trials q , is given by

$$q = \frac{1}{C_c} \int_{\zeta^*}^{\text{ZMM}} (\text{ZMM} - Z_{\min}(\xi)) dF_{Z_{\min}};$$

if

$$\int_{\zeta^*}^{\text{ZMM}} (\text{ZMM} - Z_{\min}(\xi)) dF_{Z_{\min}} < \text{CI}(\cdot), \text{ stop};$$

where ZMM is the lowest value obtained at the moment of decision,

ζ^* is the estimated value of the minimum cost,

$dF_{Z_{\min}}$ is the probability density function of the Weibull distribution,

$\text{CI}(\cdot)$ is the cost of one unit of the least expensive laboratory, and

C_c is the cost of one additional trial, including computer cost, analyst cost, etc.

It may still be in the designer's interest to examine additional decision parameters. Two of those are extensively explained by McRoberts [2]. Here we will give only some

illustration of the reasons why they are of interest.

These two parameters are the cumulative density function $F_{Z_{\min}}$ and the value $ZMM - \zeta^*$. The value of the shape parameter k , tends to describe the skewness of the distribution, as illustrated in figure 1. Assuming that areas A and B are equal, the probability of improvement $F_{Z_{\min}}$ may represent a very small absolute potential for a small k or may represent a large band of improvement for a bigger k respectively; then it may be desirable to identify regions $ZMM - \zeta^*$ and $F_{Z_{\min}}$ in the rejection range such that questionable zones may be evaluated more closely. To do so McRoberts [2] presents a plot of $ZMM - \zeta^*$ against the probability of improvement.

Figure 2 from [2] presents such a plot which is based on considering an equicost curve as a function of $F_{Z_{\min}}$, $CI(*)$ and C_c and plotted in the $F_{Z_{\min}} - (ZMM - \zeta^*)$ plane. By considering the equicost curve in isolation, the threshold decision line may be represented as intersecting the C curve at the value that may also be considered a threshold value of $Z_{\min} - \zeta^*$, the absolute range of improvement below which further search will not be feasible [2].

Zone A. A cost value point falling in here leads to a decision for continuous searching. This region is analogous to the statistical Type II error.

Zone B. Above threshold value, continue searching.



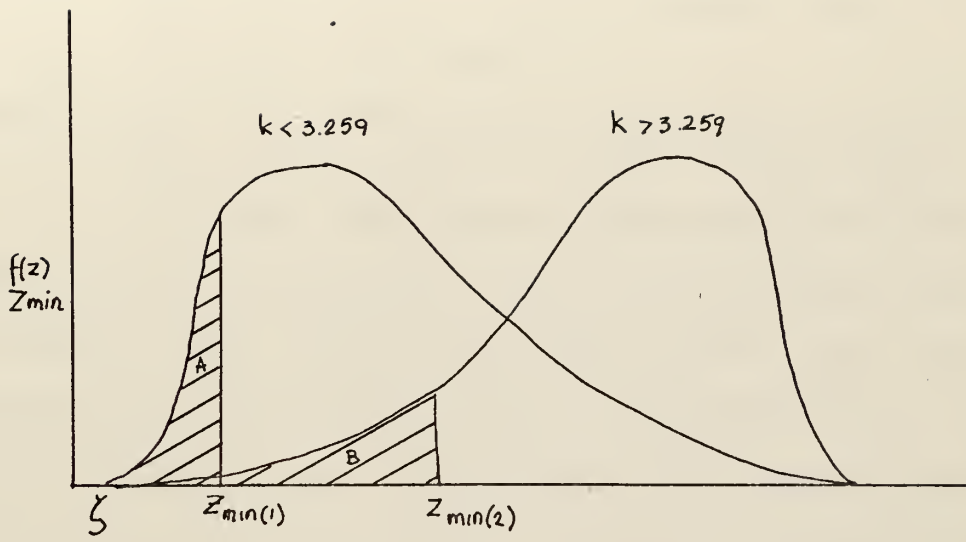


Figure 1. Effect of parameter k [2].

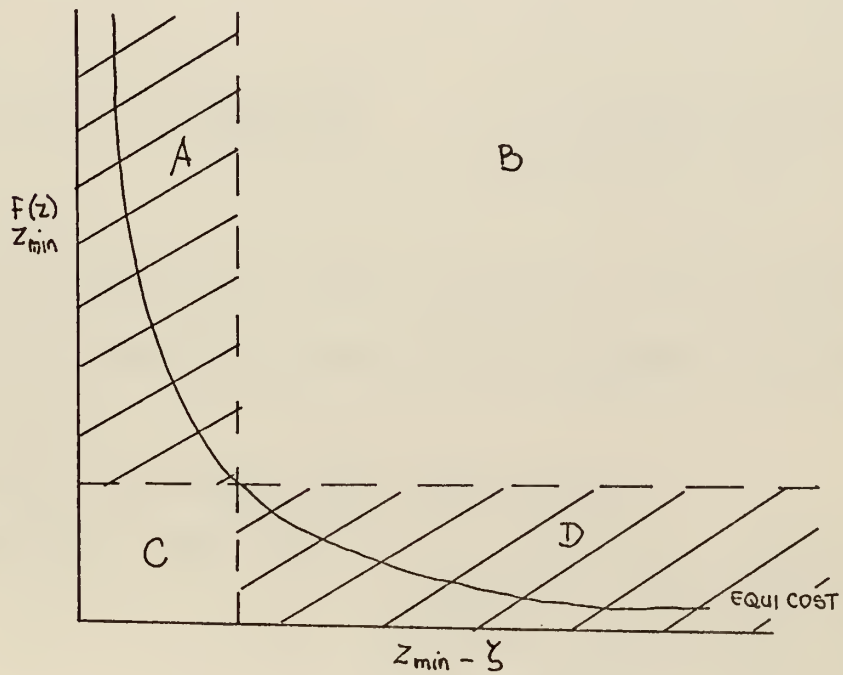


Figure 2. Decision zones for continued search [2].

Zone C. This zone lies below the threshold level to the left of the feasible absolute range. Therefore stop search.

Zone D. Here the probability of improvement may be low, but the absolute range of improvement is large. This implies continuing the search.

Other decision parameters could be the Facility Utilization Factor (UFX) and the Usage Time factor. Both have been added to the computer program. Actually they are two measures of performance. The facility utilization factor $UFX(\cdot)$ is defined as the ratio between actual requirements in hours of facility (\cdot) by all courses in the period in question and the total availability in hours of facility in the same period:

$$UFX(j) = \frac{r_{ij} \cdot N_i}{T \cdot DA_j \cdot M_j} \quad 0 \leq UFX(j) \leq 1, \\ \text{for all } j \in J.$$

The usage time factor PMAX is defined as the number of weeks that the facility is used at its maximum rate divided by $T = 50$ weeks.

Four cases are immediately self evident:

- a. UFX small, PMAX small: poor scheduling. It may be possible to eliminate one unit of that facility and consequently its cost by searching for a better schedule.

- b. UFX large, PMAX small: it is very unlikely that this case can occur. If UFX is not so large and PMAX very small, it turns out to be the previous case.
- c. UFX small, PMAX large: that implies that it may be possible to make a better use of that facility by incrementing the number of sections of the course or courses that make use of it. In the present conditions no improvements are obtained by further search.
- d. UFX large, PMAX large: implies good employment of that resource. No further improvement may be possible.

V. SOME NUMERICAL EXAMPLES AND DISCUSSION

The search procedure presented in the previous section turns out to be fairly time consuming on the computer, at least for research purposes. Hence it is necessary to make further investigations in that area as well as to refine the stopping rule if it is possible.

In order to demonstrate the method in Sections III and IV, some hypothetical problems were run by varying the number of sections of each course, without using the search procedure. The random sample was obtained by picking the least cost schedule out of a sample of ten and repeating this step $n = 100$ times.

The most economical schedule found was compared against a proposed schedule similar to that suggested by Willingham [1]. A description of that schedule is given in Appendix A.

Table 2, below, shows the results of one of those examples. It was first assumed that the availability of instructors is infinite, i.e. their initial cost was zero. That problem was compared with the results of the same schedule assuming a subjective initial cost of assigning an instructor to the school, equal for all types of instructors. In either case the proposed schedule was as good as or better than the most economical of the sample, even less than the estimated minimum cost inferred from the sample values.

Other runs were made for the same problem, this time varying the seeds for the random schedules generator, obtaining the same results explained above.

Table 3 shows the results obtained by varying the number of sections of each course.

It is interesting to point out that no schedule was found with a cost less than the one proposed in Appendix A for each case. This suggests the possibility of starting with that schedule and then applying a search procedure seeking a minimum value. Of course this might not have been the case if the heuristic procedure had been used. In addition the sample size is extremely small compared to the parent population of all possible schedules as shown in (1).

This thesis and the paper by Willingham both assumed that every section of every course used facilities evenly over its duration. The method in this thesis does not require that assumption to be made and could be easily modified to reflect more accurately the actual facility usages over time for each section. If this were done it is unlikely that a "balanced schedule" of the type described in the Appendix could so easily be found. Thus the schedule proposed in the Appendix would appear less favorable compared to the method described here.

TABLE 1

Common data for a Hypothetical School

course type	1	2	3	4	5	6	7	8	9	
duration	14	10	23	9	5	18	21	21	8	
Requirements of facility										Relative Initial cost of Facilities
1										.5
2	12	15								25.0
3			5	6			5	2		175.0
4			4	3		1	7	7		150.0
5			10	2	9	2				84.0
6								5		19.0
7						2				55.0
8						7				75.0
9									11	75.0
10	23	18								1.0
11			8							1.0
12			8							1.0
13				20						1.0
14					18	4				1.0
15						5				1.0
16						12				1.0
17					7	2				1.0
18							7	7		1.0
19							4	3		1.0
20							8	8		1.0
21							3	3		1.0
22									10	1.0
23									14	1.0

Where $G = (j: 2,3,4,5,6,7,8,9)$.

TABLE 2

COURSE TYPE	1	2	3	4	5	6	7	8	9
NUMBER OF SECTIONS	4	3	16	10	6	20	8	8	5

Problem 1

Including a subjective instructor cost (*):

PROPOSED SCHEDULE: (in Appendix A) Cost 1414.00

MOST ECONOMIC: (from sample) 1422.00

STATISTICAL INFERENCE: Estimated minimum cost 1421.98.

Weibull, shape parameter .60574.

Problem 2

Not including instructor cost:

PROPOSED SCHEDULE: (by Appendix A) 1383.00

MOST ECONOMIC: (from sample) 1383.00

STATISTICAL INFERENCE: Estimated minimum cost 1379.86.

Weibull shape parameter .66359.

(*) The differences between these two solutions was in the number of instructors required. The number of units of each type of laboratory was the same. Since the problem is to minimize the resources required, the proper way to analyse the problem is to include a cost of assigning an instructor to the school.

TABLE 3

Problem 3

COURSE TYPE	1	2	3	4	5	6	7	8	9
NUMBER OF SECTIONS	8	4	4	8	6	6	10	5	9
PROPOSED SCHEDULE: (by Appendix A) Cost									1039.00
MOST ECONOMIC: (from Sample)									1042.00
STATISTICAL INFERENCE:	Estimated minimum cost								1041.93
	Weibull shape parameter								.70306.

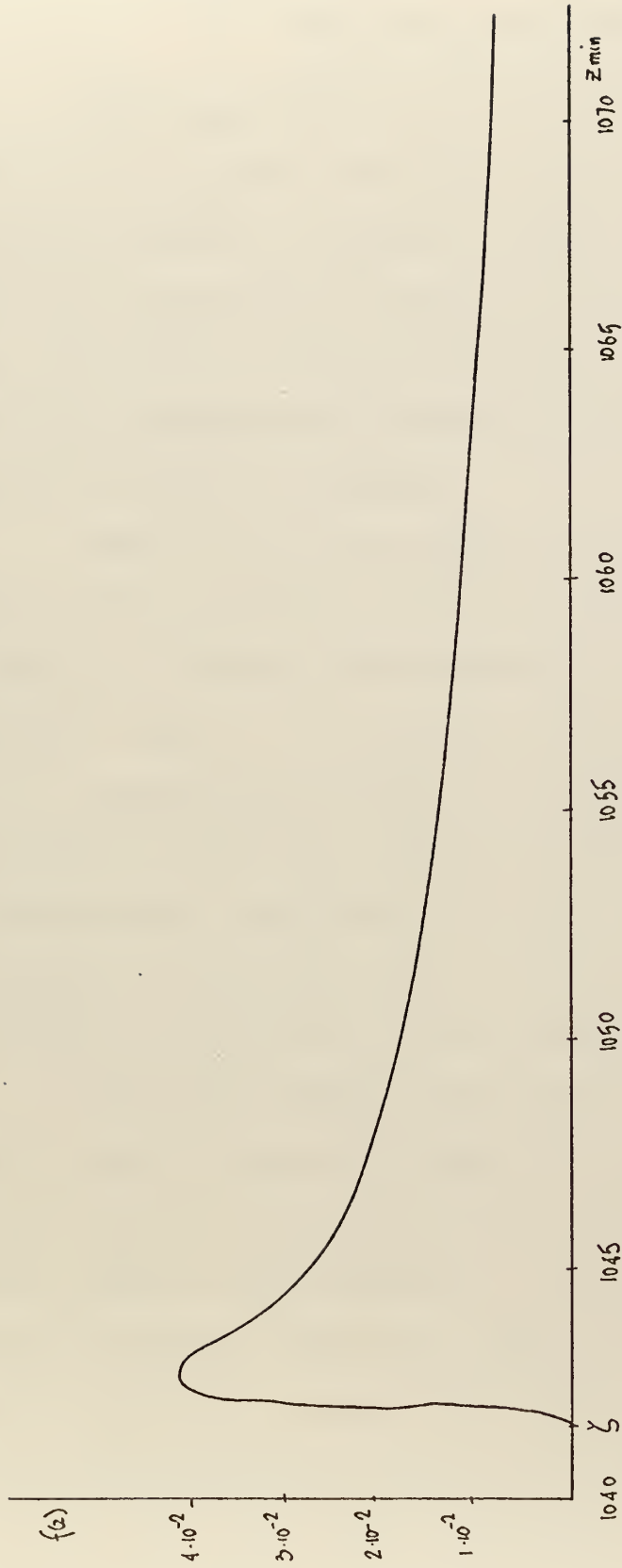


Figure 3. Probability density function obtained from sample used in problem 3 for which the result is shown in Table 3.

VI. CONCLUSION AND SUMMARY

This study addressed the problem of obtaining a schedule in a training school for the minimum cost set of facilities required, to support a given training plan, based on the quantity of students in each type of course taught. The problem was approached by making a mathematical model of the scheduling-facilities interfacing, translated later into FORTRAN IV language.

Making use of the theory of extreme-values, a sample of random minimum costs was obtained and this data was fitted to a Weibull distribution to estimate the minimum cost that it is possible to achieve.

Further investigation is required in order to come up with an efficient search procedure that assures a fast and reliable algorithm such that a minimum cost schedule is obtained by successive use of it on a random schedule drawn from the population of all feasible schedules.

The model without the heuristic procedure was tested by running several programs varying the number of sections required in a period of a year. In each case a proposed schedule (see Appendix A) was better than the most economical schedule based on a sample obtained from random schedules using the extreme-value theory, although this result would probably not hold if the courses had not been

assumed to use the facilities at a uniform rate over their duration.

From the present results it appears that a good method would be to use a schedule of the type proposed in (1) and then perhaps to apply some improving procedure to that schedule.

APPENDIX A

PROPOSING A SCHEDULE

A similar schedule has been proposed in [1] with no claim of being optimal but with the intuition that the facilities are used more or less evenly throughout the period under study.

Assume the planning period and the number of sections of each course to be taught in that period (usually a year), i.e. $T = 50$ weeks and N_i 's for all $i \in I$, are known.

Define the interval between convenings for the sections of the i^{th} course by $CS_i = [T/N_i]$, largest integer. Since the right-hand-side is seldom an exact integer define $DIF = T - N_i CS_i - 1$.

Assign to sections numbered 1 the starting date $k_{iS} = 1$ for all $i \in I$. Then the $(N_i - 1)$ sections will be scheduled to start their training CS_i weeks apart, except for DIF sections that will be scheduled $CS_i + 1$ weeks apart; it does not matter which of the $(N_i - 1)$ sections are selected. That will give a balanced schedule for each type of course in the sense of facility use.

APPENDIX B
THE COMPUTER PROGRAM

The program has been written in FORTRAN IV for the IBM 360/67 system at the Naval Postgraduate School. However, the program is self-contained and can be used in any other machine using FORTRAN IV programming language.

The program has been made in subroutines for easy further improvements or changes. In general it is composed of:

- (a) SUBROUTINE RMDATE which generates the set of random starting dates as indicated below.

Because of the assumption that any section of any course can start its instruction at any week of the year, let the random variable K_{is} be the starting date of the s^{th} section of course i . Then the probability that K_{is} be equal to $k_{is} = k$ is given by

$$P(K_{is} = k_{is}) = \frac{1}{T} \quad \text{for all } k \in K.$$

Then the cumulative distribution function is

$$\begin{aligned} P(K_{is} \leq k_{is}) &= \frac{k}{T} \quad \text{or} \\ F(k_{is}) &= \frac{k}{T} \quad \text{if } 1 \leq k \leq T \\ &= 0 \quad \text{otherwise.} \end{aligned}$$

As we can see, the distribution of K_{is} is the discrete version of the uniform distribution. Then to generate a random schedule it is only necessary to use the following modification to any uniform random number generator [0,1]:

$$K_{is} = [T \cdot RN + 0.5], \text{ largest integer,}$$

where

K_{is} is the generated (random) starting date of the s^{th} section of course i ,

T is the length in working weeks of the period that has been considered; $T = 50$ weeks per year,

RN is the uniform random number in the interval [0,1].

(b) SUBROUTINE COMPUT which computes, according to the model developed in Section I, the following values:

1. Number of units of each type of facility required to meet the specified program of training.
2. Number of weeks in which the above are actually required.
3. The total usage, in hours per year, of each facility by all courses.
4. The least cost schedule (ZMM) of the sample.

(c) The search procedure is incorporated to the main program by means of several subroutines:

1. SUBROUTINE SELECI which selects a course.
2. SUBROUTINE SELECI which selects a course.
3. SUBROUTINE REVAL which puts up-to-date the values obtained by SUBROUTINE COMPUT after a change on one starting date has been done.

(d) SUBROUTINE WEIBULL which computes the estimates indicated in Section III; namely:

1. ζ location parameter or minimum cost estimate.
2. k shape parameter.
3. v scale parameter.

(e) SUBROUTINE RULE which decides whether to stop or to continue searching. This part of the program makes use of the IBM SUBROUTINE QG9 (integration of a given function by the Gaussian quadrature method, nine points formula) which has been added under the name SUBROUTINE RULE. This subroutine also determines how many additional trials should be done, if any.

One of the features of the program is that one or more predetermined schedules can be tested in case there exist constraints in the scheduling period.

The program also gives a write-up of each tested schedule and the most economical schedule, including characteristic values as utilization factors, usage percentage and weekly requirements of facilities in units of facilities.

All data is fed to the program by means of DATA STATEMENTS at the beginning of it, except course requirements and the proposed schedules that are fed by means of Data Cards. The arrangement of the data cards is as follows:

1. The first card has the value of two program control parameters, ST and SNO. ST indicates the number of proposed schedules that the programmer or decision-maker wishes to test. SNO indicates whether search procedure is desired or not.
2. The next set of cards are course requirements, one for each type of facility.
3. Finally are the proposed schedule cards. Each card contains the section's starting dates of one course.

READ IN PROGRAM CONTROL INDICATORS

1 READ(5,1) ST, SNO
FORMAT(2I5)

READ FACILITY REQUIREMENTS FOR ALL COURSES

DO 10 I=1,L
READ(5,11)(R(I,J), J=1,MJ)
11 FORMAT(1X,30I2)
10 CONTINUE

35 IF(ST.EQ.0) GO TO 39
TOT=0
ST=ST-1
SCH= SCH+1
NR=1
NT= 1

IF THERE ARE SCHEDULES TO BE TESTED READ IN THE FIRST SCHEDULE

15 DO 16 I=1,L
SI=N(I)
READ(5,17)(KS(I,S), S=1,SI)
17 FORMAT(1X,20I3)
16 CONTINUE

GO TO 25
39 IF(SNO.EQ.0) STOP
TOT=1
LIGHT= 1
NR= NRD
NT= NTD
NR1= 1

25 DO 30 T1= NR1, NR
IF(TOT.EQ.0) GO TO 75
CALL RMDATE(L,N,KS,IR,LR,MR,ML,LIGHT,TIME)
LIGHT= 0

ALL STARTING POINTS FOR A GIVEN SET OF SECTIONS ARE NOW DETERMINED
START COMPUTATIONS

75 CALL COMPUT(TIME,L,N,KS,D,MJ,DA,R,KMAX,KOUNT1,RQMNT,MAX,MJ1,CI,
CZMIN,KSM,ZMM,ZM1,T1,NR,KS1)

REDUCING COST PROCEDURE

```

IF(NR.EQ.1) GO TO 30
CALL SELECI(TIME,MJ1,KOUNT1,CI,IND)
MJ2= MJ1- 1

DO 2001 JD=1,MJ2
JK1= IND(JD)
IF(JK1.LE.1.OR.KOUNT1(JK1).GT.24.OR.JK1.GT.MJ1) GO TO 2001
IF(MAX(JK1).LE.1) GO TO 2001
CALL SELECI(IND,R,L,JK1,RT1,IJ)
IF(IJ.LE.1) GO TO 2001
DO 2002 I=1,IJ
LP= RT1(I)

SI= N(LP)
DO 2003 LS=1,SI
DO 2004 K=1,TIME
KS(LP,LS)= K
CALL REVAL(TIME,LP,N,KS,D,KSM,R,MJ,MJ1,DA,MAX,CI,LS,KMAX,TI,
80 C KOUNT1,ZMIN,ZMM,KS1)
IF(KOUNT1(JK1).GT.24) GO TO 2001
2004 CONTINUE
2003 CONTINUE
2002 CONTINUE
2001 CONTINUE
30 CONTINUE

DO 2200 J=1,MJ
PMAXP(J)= FLOAT(KOUNT1(J))/FLOAT(TIME)*100.0
IF(MAX(J).GT.0) GO TO 2210
UFX(J)= 9999999999.9
GO TO 2200
2210 UFX(J)= FLOAT(RQMNT(J))/FLOAT(MAX(J)*DA(J)*TIME)
2200 CONTINUE

NOW PRINT THE RESULTS
*****

CALL PRINT(SND,TOT,SCH,ZMIN,ZMM,ZM1,NR,NT,MJ,MAX,UFX,PMAXP,KOUNT1,
CL,N,KSM,KMAX,TIME)

IF(TOT.EQ.1) GO TO 3100
IF(ST)3150,35,35

COMPUTE AGAIN COST AND CHARACTERISTICS OF MOST ECONOMIC SCHEDULE

```



```

3100 DO 1400 I=1,20
DO 1500 S=1,20
KS(I,S)= KSI(I,S)
1500 CONTINUE
1400 CONTINUE
SI=-1
SCH= 99
TOT= 0
NR= 1
NT= 1
GO TO 25
3150 CALL WEIBUL(NRD,ZMIN,SCALE,EPSLON,SHAPE)
STOPPING RULE
*****
CALL RULE(SCALE,EPSLON,SHAPE,ZMM,CCRT,CCOST,NQ)
IF(NQ.LT.1) STOP
NR1= NR + 1
NR= NR+ NQ
GO TO 25
END

```


MJ1 ONE PLUS NUMBER OF DIFFERENT TYPES OF LABORATORIES
(LAB. TYPE FACILITIES) REQUIRED

CI(J) INSTALATION COST OF ONE UNIT OF FACILITY J

ZMIN SAMPLE OF A LOCAL MINIMUM COST SCHEDULE OBTAINED FROM
THE SEARCH PROCEDURE

KSM(,) STARTING DATES OF THE MOST ECONOMICAL SCHEDULE FOUND

ZMM COST OF FACILITIES FOR THE ABOVE SCHEDULE

ZM1 FACILITIES COST OF ANY PROPOSED SCHEDULE

T1 SAMPLE NUMBER

KSI(,) STARTING DATES OF ANY PROPOSED SCHEDULE

IMPLICIT INTEGER#4(D,R,T)
INTEGER#4(S,SNO,S,SI,SCH)
DIMENSION N(20),KS(20,20),D(20),DELTA(20),RJ(30),R(20,30),MAX(30),
CROMT(30),M(30),KMAX(30,50),KOUNTI(30),DA(30),CI(30),ZMIN(100),
CKSM(20,20),KMA(30,50),KOUNT(30),RQMAD(30),KSI(20,20)

DO 90 J=1,MJ
MAX(J)=0
KOUNT(J)=0
RJ(J)=0
M(J)=0
RQMAD(J)=0
90 CONTINUE

DO 100 K=1,TIME
DO 300 I=1,L
DELTA(I)=0
SI=N(I)

IS SECTION S OF COURSE I AT HOME DURING WEEK K?

DO 400 S=1,SI
IF(K-KS(I,S)) 450,500,550
IF(KS(I,S)+D(I)-K-TIME-1)400,500,500
550 IF(KS(I,S)+D(I)-K-1) 400,500,500
500 DELTA(I)=DELTA(I)+1
400 CONTINUE

COMPUTE THE TOTAL AMOUNT OF FACILITY J REQUIRED IN WEEK K

```

300 CONTINUE
DO 200 J=2,MJ
DO 350 I=1,L
RJ(J)=R(I,J)*DELTA(I)+RJ(J)
CONTINUE
350 IF(J.LE.MJ1) GO TO 200
RJ(I)=RJ(I)+RJ(J)
200 CONTINUE

```

HERE WE COMPUTE THE NUMBER OF FACILITIES J REQUIRED TO MEET THE DEMAND

```

DO 650 J=1,MJ
J1=0
JJ=J1+1
IF(RJ(J).GT.J1*DA(J)) GO TO 600
M(J)=JJ
IF(RJ(J).EQ.0) M(J)=0
RQMAD(J)=RQMAD(J)+RJ(J)
IF(M(J).LT.MAX(J)) GO TO 199
IF(M(J).EQ.MAX(J)) GO TO 198
MAX(J)=M(J)
KOUNT(J)=1
GO TO 199
198 KOUNT(J)=KOUNT(J)+1
199 KMA(J,K)=M(J)
RJ(J)=0
M(J)=0
CONTINUE
650 CONTINUE
100 CONTINUE
ZM=0.0
DO 1100 J=1,MJ
ZM=ZM+MAX(J)*CI(J)
CONTINUE
1100

```

HERE WE SAVE THE VALUE OF THE MINIMUM COST OF THE RUN

```

ZM1=ZM
IF(NR.EQ.1) GO TO 1150
IF(ZMIN(T1).LE.ZM) RETURN
ZMIN(T1)=ZM
1150 IF(ZMM.LT.ZM) GO TO 1175

```

THIS IS THE MOST ECONOMICAL SCHEDULE FOUND

ZMM= ZM


```

DO 1180 I=1,L
SI=N(I)
DO 1190 S=1,SI
KS(I,S)=KS(I,S)
CONTINUE
CONTINUE
1190
1180

SAVE THE SCHEDULE WITH THE LEAST COST ACCORDING TO THE SEARCH PROCEDURE

1175 DO 1200 I=1,L
SI=N(I)
DO 1300 S=1,SI
KSM(I,S)=KS(I,S)
CONTINUE
1300

TI1=SI
DO 1350 S=1,SI
TI1=TI1-1
IF(TI1.LT.1) GO TO 1350
DO 1375 T2=1,TI1
T3=T2+1
IF(KSM(I,T2).LE.KSM(I,T3)) GO TO 1375
KTEMP=KSM(I,T2)
KSM(I,T2)=KSM(I,T3)
KSM(I,T3)=KTEMP
CONTINUE
CONTINUE
1375
1350
1200

DO 1400 J=1,MJ
KOUNT1(J)=KOUNT(J)
RQMNT(J)=RQMAD(J)
DO 1450 K=1,TIME
KMAX(J,K)=KMA(J,K)
CONTINUE
CONTINUE
1450
1400

RETURN
END

```



```

SUBROUTINE WEIBUL(NRD,ZMIN,SCALE,EPSSLON,SHAPE)
*****
PURPOSE  THIS SUBROUTINE ESTIMATES THE PARAMETERS OF A WEIBULL DISTRI-
         BUTION BASED ON THE MINIMUM SUM OF THE SQUARES ABOUT THE
         REGRESSION LINE.
LOG(Z- EPSSLON)- LOG(SCALE- EPSSLON)=
      =(1/SHAPE)*LOG(-LOG(1.0-F(Z)))
WHERE
EPSSLON: A CONSTAN EQUAL TO THE LOWEST VALUE EXTREME VALUE
SCALE    A CONSTANT PARAMETER INDICATING THE VALUE OF THE
         OR LOCATION PARAMETER OF THE DISTRIBUTION
         VARIABLE SUCH THAT THE PROBABILITY THAT THE EXTREME
         VALUE IS EQUAL TO OR LESS THAN SCALE IS APPROXIMATELY
         0.63, REFERRED TO AS THE CHARACTERISTIC SMALLEST
         VALUE IN EXTREME-VALUE THEORY
(SCALE-EPSSLON) IS THE IS THE DISTRIBUTION'S
SCALE PARAMETER
SHAPE    A CONSTANT PARAMETER INDICATING THE SHAPE OF THE
         DISTRIBUTION
ARGUMENTS
NRD      NJMNER OF OBSERVATIONS
ZMIN     SAMPLE OF A LOCAL MINIMUM COST SCHEDULE OBTAINED FROM
         THE SEARCH PROCEDURE
IMPLICIT INTEGER*4(D,R,T)
INTEGER*4SIZE,FLAG
INTEGER*4ST,SNO,S,SI,SCH
DIMENSION FZ(100),C(100), A(100), CESTM(100),TCOUNT(100)
DATA ABAR/0.0/,CBAR/0.0/,AC/0.0/,A2/0.0/,C2/0.0/,SUM/0.0/
DATA JUMP/0/, FLAG/0/, F2/0.0/,TCOUNT/100#0/
ORDERING THE COST SAMPLES ACCORDING TO THEIR INCREASING SIZE
SIZE= NRD
NI= NRD
DO 3000 I=1,SIZE
NI= NI- 1

```



```

DO 3200 T2=1,N1
T3= T2+ 1
IF(ZMIN(T2).LE.ZMIN(T3)) GO TO 3200
ZTEMP= ZMIN(T2)
ZMIN(T2)= ZMIN(T3)
ZMIN(T3)= ZTEMP
CONTINUE
CONTINUE
3200
3000

```

GROUPING THE DATA AND OBTAINING ITS FREQUENCY

```

TN= 1
IF(TN.GT.SIZE) GO TO 3675
I1= TN
DO 3600 T1= I1,SIZE
TMIN=FIX(ZMIN(T1)*100.0)
TMIN2= FIX(ZMIN(TN)*100.0)
IF(TMIN-TMIN2) 3625,3650,3600
WRITE(6,3626)
FORMAT(1X,/,20X,'ERROR IN LOOP "3600"',/)
RETURN
TCOUNT(TN) = TCOUNT(TN) + 1
CONTINUE
TN= TN+ TCOUNT(TN)
GO TO 3500
TC= 0
DO 3700 T=1,SIZE
IF(TCOUNT(T))3725,3700,3775
WRITE(6,3726)
FORMAT(1X,/,20X,'ERROR IN LOOP "3700"',/)
RETURN
TC= TC+ 1
TCOUNT(TC) = TCOUNT(T)
ZMIN(TC)= ZMIN(T)
CONTINUE
3625
3626
3650
3600
3675
3725
3726
3775
3700

```

ESTIMATING THE VALUES OF THE CUMULATIVE DISTRIBUTION FUNCTION

```

F1= 1.0/FLOAT(SIZE+1)
DO 3300 T2= 1,TC
F2= F2+ TCOUNT(T2)*F1
FZ(T2)= F2
C(T2)=ALOG(-ALOG(1.0- FZ(T2)))
CONTINUE
3300
EPSLON= ZMIN(1)
ZRANGE= ZMIN(TC) - ZMIN(1)

```



```

STEP= ZRANGE/ 100.0
ALT= STEP/1000
EPSLON=EPSLON- STEP
4300

DO 4400 T=1,TC
A(T)= ALOG(ZMIN(T)-EPSLON)
CONTINUE
4400

REGRESSION LINE ESTIMATION

DO 4500 T3=1,TC
ABAR= ABAR +A(T3)
CBAR= CBAR +C(T3)
AC= AC +C(T3)*A(T3)
A2= A2 +A(T3)*A(T3)
C2= C2 +C(T3)*C(T3)
CONTINUE
4500

SIZE= TC
SLOPE=(AC- ABAR*CBAR/SIZE)/(A2- ABAR*ABAR/SIZE)
AVAR= (A2- ABAR*ABAR/SIZE)/(SIZE- 1)
CVAR= (C2- CBAR*CBAR/SIZE)/(SIZE- 1)
B= (ABAR- CBAR/SLOPE)/ SIZE

OBTAINING THE SUM OF THE SQUARE DIFFERENCES

DO 4600 T4=1,TC
CESTM(T4)= CBAR/SIZE +SLOPE*(A(T4)- ABAR/SIZE)
SUM= SUM + (C(T4) - CESTM(T4))* (C(T4) - CESTM(T4))
CONTINUE
4600

IF THE ESTIMATE OF EPSLON DOES NOT YIELD THE MINIMUM SUM OF THE SQUARE
DIFFERENCES, TRY AGAIN WITH ANOTHER EPSLON UNTIL OBTAIN SO

IF(JUMP.EQ.1) GO TO 4700
SQRMIN= SUM
SHAPE= SLOPE
SCALE= EXP(B)+ EPSLON
JUMP= 1

4700 IF(SUM.LT.SQRMIN) GO TO 4800
IF(FLAG.EQ.1) GO TO 4900
ABAR= 0.0
CBAR= 0.0
AC= 0.0
A2= 0.0
C2= 0.0
SUM= 0.0

```



```

FLAG=1
GO TO 4300

4800  SQRMIN= SUM
      SHAPE= SLOPE
      SCALE= EXP(B)+ EPSLON
      ABAR= 0.0
      CBAR= 0.0
      AC= 0.0
      A2= 0.0
      C2= 0.0
      SUM= 0.0
      GO TO 4300

4900  IF (STEP.LT.ALT) GO TO 9800
      EPSLON= EPSLON+ 2*STEP
      STEP= STEP/10.0
      ABAR= 0.0
      CBAR= 0.0
      AC= 0.0
      A2= 0.0
      C2= 0.0
      SUM= 0.0
      FLAG= 0
      JUMP= 0
      GO TO 4300

9800  NR= NRD
      NT= NTD
      WRITE(6,3400)NR,TC,(ZMIN(J)),J1=1,TC)
3400  FORMAT('1',//,20X,'SAMPLE SIZE',15,6X,
           C',13,/,20X,,'*****REduced SAMPLE SIZE WEIBULL
           C//,20X,'ORDERED MINIMUM COSTS',/,(',20X,5F15.3))

3450  WRITE(6,3450)(TCOUNT(J),J=1,TC)
      FORMAT('0',19X,'SAMPLE FREQUENCIES',/,(',16X,5I15))

9900  WRITE(6,9900)EPSLON,SHAPE,SCALE
      FORMAT('1',//,20X,'PARAMETERS WEIBULL DISTRIBUTION',/20X,'*****
      C*****
      C//,20X,'SHAPE PARAMETER:',8X,F15.5,/,20X,'SCALE PARAMETER:',8X,F
      C15.5)
      RETURN
      END

```



```

SUBROUTINE RMDATE(L,N,KS,IR,LR,MR,ML,LIGHT,TIME)
** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** ** *
PURPOSE THIS SUBROUTINE GENERATES RANDOM STARTING DATES FOR ALL
ARGUMENTS SECTIONS OF ALL COURSES.
L NJMBER OF DIFFERENT TYPES OF COURSES
N(I) NUMBER OF SECTIONS TO BE TRAINED OF COURSE I DURING
THE PERIOD "TIME".
KS(,) STARTING DATE OF THE S-TH SECTION OF COURSE TYPE I

IR FIVE DIGITS ODD NUMBER
LR " " " " "
MR " " " " "
ML " " " " "

LIGHT SENSOR=1 AT THE BEGINNING OF THE PROGRAM
0 THERE AFTER

TIME NUMBER OF WEEKS OF PLANNING PERIOD

INTEGER*4S,SI,TIME
DIMENSION N(20),KS(20,20),NI(128)
DATA IK/65539/,MM/33554433/,MN/36243609/
IF(LIGHT.EQ.0)GO TO 80
DO 40 IG=1,128
IR=IR*IK
NI(IG)=IR
CONTINUE
DO 70 I=1,L
SI=N(I)
DO 60 S=1,SI
LR=LR*ML
MR=MR*MM
JR=(IABS(LR)/16777216)+1
GNR=0.5+FLOAT(NI(JR)+LR+MR)*2.328306 E-10
IK=IK*MN
NI(JR)=IK
KS(I,S)=FIX(TIME*GNR+0.5)
IF(KS(I,S).LT.1)KS(I,S)=1
IF(KS(I,S).GT.50)KS(I,S)=50
CONTINUE
RETURN
END
40
60
70

```



```

SUBROUTINE PRINT(SNO,TOT,SCH,ZMIN,ZMM,ZM1,NR,NT,MJ,MAX,AFX,PMAXP,
CKOUNT1,L,N,KSM,KMAX,TIME)
*****
IMPLICIT INTEGER*4(D,R,T)
INTEGER*4ST,SNO,S,SI,SCH
DIMENSION ZMIN(100),MAX(30),AFX(30),PMAXP(30),KOUNT1(30),N(20),
CKSM(20,20),KMAX(30,50)

IF(SNO.EQ.1.AND.TOT.EQ.1) GO TO 8900
IF(SCH.NE.99) GO TO 8700

WRITE(6,8600) ZMM
FORMAT(1,/,/,20X, ' THIS IS THE MOST ECONOMICAL SCHEDULE FOUND',/,
C20X, '*****',/,/,20X, 'FACILITIES',/,/,20X, 'FACILITY
CES INSTALLATION COST=',F15.3,/)
GO TO 9150

8700 WRITE(6,8800)SCH, ZM1
8800 FORMAT(1,/,/,20X, 'PROPOSED SCHEDULE NUMBER',I3,/,20X, '*****',
C*****',/,/,20X, 'FACILITIES INSTALLATION COST=',F15.3,/)
GO TO 9150

8900 SNO= 0
WRITE(6,9000)NR,NT,(ZMIN(J1),J1=1,NR)
FORMAT(1,/,/,20X, 'SAMPLE SIZE',I5,6X, 'NUMBER OF TRIALS PER SAMPLE
C,I3,/,20X, '*****',/,/,20X, 'MINIMUM COSTS SAMPLE',/,('0',13X,5F15.3))
C//,20X, '*****'
RETURN

9150 WRITE(6,9400)(J,MAX(J),J=1,MJ)
FORMAT(1X,/,/,20X, 'FACILITIES REQUIRED',/,( ' ',20X,5(I2, ' '),15,7X
" ))

9500 WRITE(6,9500)(J,AFX(J),J=1,MJ)
FORMAT(1X,/,/,20X, 'FACILITIES UTILIZATION FACTOR UFX(J)',/,( ' ',20X
C,5(I2, ' '),F5.3,7X))

9600 WRITE(6,9600)(J,PMAXP(J),J=1,MJ)
FORMAT(1X,/,/,20X, 'USAGE TIME (PERCENTILE) OF MAX(J)',/,( ' ',20X,5(
C12, ' '),F7.3,5X))

9700 WRITE(6,9700)(J,KOUNT1(J),J=1,MJ)
FORMAT(1X,/,/,20X, 'NUMBER OF WEEKS WHEN MAX(J) IS REQUIRED',/,( ' ',
C20X,5(I2, ' '),15,7X))

```



```

DO 1200 I=1,L
SI=N(I)
T11=SI
DO 1350 S=1,SI
T11=T11-I
IF(T11.LT.1) GO TO 1350
DO 1375 T2= 1, T11
T3= T2+ I
IF(KSM(I,T2).LE. KSM(I,T3)) GO TO 1375
KTEMP= KSM(I,T2)
KSM(I,T2)= KSM(I,T3)
KSM(I,T3)= KTEMP
1375 CONTINUE
1350 CONTINUE
1200 CONTINUE

WRITE(6,9706)
FORMAT(1X,/,/,20X,' SECTIONS STARTING DATES SCHEDULED',)
DO 9702 I=1,L
SI= N(I)
WRITE(6,9701)(KSM(I,S),S=1,SI)
FORMAT(20X,20I4)
9701 CONTINUE
9702 CONTINUE

WRITE(6,9705)(J,J=1,MJ)
FORMAT(1X,/,/,20X,' WEEKLY LOAD',/,25X,30I3)
WRITE(6,9707)
FORMAT('O',)
DO 9703 K=1, TIME
WRITE(6,9704)K,(KMAX(J,K),J=1,MJ)
FORMAT(20X,I3,2X,30I3)
9703 CONTINUE

RETURN
END

```



```

SUBROUTINE SELECJ(TIME,MJ1,KOUNT1,CI,IND)
*****

```

```

PURPOSE THIS SUBROUTINE SELECTS THAT FACILITY (OF LAB TYPE) WITH
SMALLEST USAGE FACTOR OF THE MAXIMUM REQUIRED IN THE CONSIDERED
PERIOD OF TIME. I.E. THAT FACILITY WITH KOUNT1(.) INDEX
IS SMALLER.

```

```

ARGUMENTS
TIME NUMBER OF WEEKS OF PLANNING PERIOD
MJ1 ONE PLUS NUMBER OF DIFFERENT TYPES OF LABORATORIES
(LAB. TYPE FACILITIES) REQUIRED
KOUNT1 INDICATES NUMBER OF WEEKS WHEN THE MAXIMUM NUMBER OF UNITS
OF FACILITY J IS USED
CI(J) INSTALLATION COST OF ONE UNIT OF FACILITY J

```

```

IND(N) INDEX WHICH VALUE IS THE NUMBER DESIGNATION OF A FACILITY
AND ITS ARGUMENT N INDICATES THE ORDERING OF THE FACILITIES
BY SMALLEST USAGE TIME AND MORE EXPENSIVE INSTALLATION COST

```

```

IMPLICIT INTEGER*4(D,R,T)
INTEGER*4S1,SNO,S,SI,SCH
DIMENSION KOUNT1(30),CI(30),IND(30)
JK= 0
NO= 1
DO 1000 K=1, TIME
DO 1001 J=2, MJ1
IF(KOUNT1(J).EQ.K) GO TO 1003
GO TO 1001
JK= JK+ 1
IND(JK)= J
CONTINUE
IF(JK.LE.NO) GO TO 1006
N1= JK
DO 1004 I= NO, JK
N1= N1- 1
IF(N1.LT.NO) GO TO 1004
DO 1005 N2= NO, N1
N3= N2+ 1
N4= IND(N2)
N5= IND(N3)
IF(CI(N4).LE.CI(N5)) GO TO 1005

```

1003

1001


```
IND(N2) = IND(N3)
IND(N3) = NTEMP
CONTINUE
CONTINUE
NO= JK+ 1
CONTINUE
RETURN
END
```

```
1005
1004
1006
1000
```



```

1010 T2= 1, IJ1
T3= T2 +1
IF (RT(T2), GE, RT(T3)) GO TO 1010
RTEMP1= RT(T2)
RT(T2)= RT(T3)
RTI(T2)= RTI(T3)
RT(T3)= RTEMP
RTI(T3)= RTEMP1
CONTINUE
CONTINUE
RETURN
END
1010
1009

```


ZMIN SAMPLE OF A LOCAL MINIMUM COST SCHEDULE OBTAINED FROM THE SEARCH PROCEDURE

ZMM, COST VALUE OF THE MOST ECONOMICAL SCHEDULE FOUND AT THE MOMENT OF THE DECISION

KS1(,) STARTING DATES OF ANY PROPOSED SCHEDULE

```

IMPLICIT INTEGER*4(D,R,T)
INTEGER*4ST,SNO,S,SI,SCH
DIMENSION N(20),KS(20,20),D(20),KSM(20,20),RJ(30),R(20,30),DA(30),
CM(30),MAX(30),RJMAX(30),KMAX(30,50),CI(30),KOUNT1(30),ZMIN(100),
CKSI(20,20)
DATA DELT1/0/,DELT2/0/,RTEST/0/,RJ/30*0/,M/30*0/

DO 100 K=1,TIME
SI=N(LP)
DO 400 S=1,SI
IF(K-KS(LP,S))450,500,550
IF(KS(LP,S)+D(LP,S)-K-TIME-1) 400,500,500
500 IF(KS(LP,S)+D(LP,S)-K-1) 400,500,500
400 DELT1=DELT1+ 1
CONTINUE

DO 401 S=1,SI
IF(K-KSM(LP,S)) 451,501,551
IF(KSM(LP,S)+ D(LP,S)-K-TIME- 1) 401, 501,501
501 IF(KSM(LP,S)+D(LP,S)-K-1) 401,501,501
401 CONTINUE

IF(DELT2.LE.DELT1) GO TO 390
DO 200 J=2,MJ
RJ(J)=R(LP,J)#DELT1+ RJ(J)
IF(J.LE.MJ1) GO TO 200
RJ(1)=RJ(1)+ RJ(J)
200 CONTINUE

DO 650 J=1,MJ
JI= 0
IF(RJ(J).GT.J1#DA(J)) GO TO 600
M(J)=JI
IF(RJ(J).EQ.0) M(J)= 0
IF(M(J)- MAX(J)) 370,390,390
IF(M(J)- KMAX(J,K)) 380,390,390
370 KOUNT1(J)= KOUNT1(J)- 1
380

```



```

381 IF(KOUNT1(J)) 381,381,383
KOUNT1(J)=50
383 MAX(J)=MAX(J)-1
KMAX(J,K)=M(J)
RJ(J)=0
M(J)=0
RTEST=0
650 CONTINUE
390 DELT1=0
100 DELT2=0
CONTINUE

IF(RTEST.EQ.0) RETURN
ZM=0.0
DO 1100 J=1,MJ1
ZM=ZM+MAX(J)*CI(J)
1100 CONTINUE

IF(ZMM.GT.ZM) KS1(LP,LS)=KS(LP,LS)
IF(ZMIN(T1).LE.ZM) RETURN
ZMIN(T1)=ZM
KSM(LP,LS)=KS(LP,LS)
RETURN
END

```




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13. ABSTRACT

The problem of determining the quantity of classrooms, laboratories and instructors to train sections of students attending numerous distinct courses in a school such as the Fleet Ballistic Missile School is considered.

A procedure is developed for determining feasible schedules in order to graduate a fixed number of trainees over time while minimizing the cost of facilities mix required.

14.

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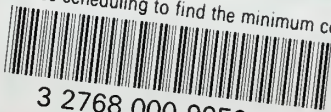
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